

Drinking water temperature modeling in domestic systems

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Abstract

Domestic drinking water systems are the final stage of the transport process to deliver potable water to the customer's tap. Although these systems play an important role in drinking water quality, only several researches on the effect of residence time and temperature were performed during the past. These two parameters play an important role in microbial growth and metal leaching. Past research was performed on the appearance of *Legionella* in domestic drinking water systems, occurrence of hotspots which influence the drinking water temperature and the microbial growth and leaching of metals in stagnant water. However, the fluid dynamics which are present in domestic drinking water systems due to highly variable demand patterns were not included yet. By the use of SIMDEUM consumer demand patterns could be modeled, and drinking water dynamics can be approached. The Dutch legislation on drinking water prescribes the temperature at the tap should not exceed the threshold of 25°C. However, any scientific basis for this threshold was not found in the literature. Nor could it be obtained from interviews with experts. During this master thesis research a model was developed to calculate the temperature in domestic drinking water systems. Afterwards several scenarios were calculated to investigate the effects of e.g. hot summer days, pipe concealment, housing types and hotspots on the drinking water temperature. This research is a first exploration in the field of drinking water temperature modeling in domestic systems, since empirical data on temperature in domestic drinking water systems is not available. It was found that residence time influences the microbial growth more than temperature does. Demand pattern changes in time have more influence than demand volume changes since water in the domestic drinking water system is heated relatively fast. The results of this research have consequences for the in-house sampling method of Dutch water companies (RDT sampling) which is used to measure the water temperature within the drinking water supply system before the water meter. Water is heated while it passes the domestic drinking water system before it is sampled at the kitchen tap. Hence the actual temperature in the drinking water distribution system will be lower than RDT measurements show.

Preface

The purpose of this research is to determine the drinking water temperature within the domestic infrastructure by modeling. Next to peak velocity, residence time and initial concentration of substances, temperature is one of the most important parameters which influence the water quality. Temperature has direct influence on microbial growth and the chemical and physical properties of drinking water.

The rationale of this master thesis research was formed by the research *Future permanence of the drinking water infrastructure* which was performed by the department of Waterinfrastructure (WIS) of KWR Watercycle Research Institute in 2013. This master thesis research on *Drinking water temperature modeling in domestic systems* was performed parallel to this research during an internship at KWR Watercycle Research Institute.

I would like to thank my thesis committee because of their willingness and the time they spend to counsel my research. A special thanks goes out to Will Scheffer for his willingness to provide me a broad introduction on sanitation engineering in practice during the last sixty years.

July 2013,
Andreas Moerman

Content

Abstract	3
Preface	5
Content	7
List of abbreviations	9
Glossary	11
1 Introduction	13
1.1 Available data and research on domestic drinking water temperature	13
1.2 Relevance for water companies and installation companies	14
1.3 Research questions	14
2 Problem description	15
3 Approach and methods	17
3.1 Introduction	17
3.2 Temperature modeling	17
3.3 Introduction to domestic drinking water systems	18
3.4 Consequences of temperature increase	22
3.5 Modeling temperature in domestic drinking water systems	22
3.6 Heat transfer model	25
4 Results	35
4.1 Explanation of used graphs	35
4.2 Reference case vs. summer day	35
4.3 Different housing types	37
4.4 Effects pipe concealment	38
4.5 Hotspot simulation	39
4.6 Relation temperature and demand volumes	42
4.7 Temperature during water demand	43
5 Discussion	45
5.1 Temperature model	45
5.2 Models for microbial growth	45
5.3 Results	45
5.4 Model applications	47
6 Conclusions and recommendations	49
References	51
List of variables	55

Annex I	57
• Brief introduction on water quality within the domestic drinking water system	57
Annex II	61
• Legislation and standards in drinking water distribution	61
Annex III	67
• Figures for bathroom washstand and toilet washbasin	67
• Pipe characteristics of used networks	75
Annex IV	77
• MSX code	77
• Feedback on use of the EPANET MSX	80
• Input parameters	81
Curriculum Vitae author	83

List of abbreviations

AOC	Assimilable organic carbon; indicator of potential microbial regrowth.
Dwb	Drinkwaterbesluit, Dutch drinking water decree; elaboration of Dww.
DWDS	Drinking water distribution system.
DWTP	Drinking water treatment plant.
Dww	Drinkwaterwet, Dutch directive on drinking water.
DDWS	Domestic drinking water system; the infrastructure within a house to deliver the drinking water from the service pipe (connection point: check valve/water meter) to the tap. <i>Dutch: woninginstallatie.</i>
DDWT(M)	Domestic drinking water temperature (modeling)
ISSO	Knowledge institute for branch of installers/fitters.
RIVM	Rijksinstituut voor volksgezondheid en milieu; governmental institute for public health and environment.
TNO	Nederlandse organisatie voor toegepast wetenschappelijk onderzoek; Dutch organization for applied scientific research.
VEWIN	Vereniging van waterbedrijven in Nederland, association of drinking water companies in the Netherlands.
Uneto-VNI	Branch organization for installers of domestic electrical and plumbing systems.

Glossary

Demand volume	Volume of water which is drawn from a tap when a demand occurs.
Drinking water distribution system	Drinking water infrastructure from treatment plant to water meter; water company's property.
Domestic drinking water system	Drinking water infrastructure from water meter to several taps; customers property.
EPANET	Open source program to perform hydraulic calculations on pressurized networks.
Heterotrophic plate count (HPC)	Unit which is used to measure the number of heterotrophic bacteria in drinking water.
MSX (Multi Species Extension)	Open source software tool to perform water quality calculations.
Random daytime sampling	Measuring protocol for drinking water companies to monitor the leaching of metals in DDWS.
SIMDEUM	SIMulation of water DEMand, and End Use Model; software developed by KWR to model drinking water demand patterns.

1 Introduction

Clean and safe drinking water is one of the most important necessities for a well-organized society. In former research on the relation of drinking water supply and water quality the focus was mostly on drinking water distribution systems. However, the domestic drinking water system also influences the water quality through high residence times (Lautenschlager, Boon et al. 2010), leaching of metals (Slaats, Blokker et al. 2008), hydraulic regimes (Douterelo, Sharpe et al. 2013), and material use (Rogers, Dowsett et al. 1994, Lehtola, Miettinen et al. 2004, Oesterholt, Veenendaal et al. 2007, Moritz, Flemming et al. 2010). Drinking water passes this domestic drinking water system before it enters the tap to be used for flushing, washing, cleaning, drinking or cooking.

Figure 1.1.1 shows the four major parameters which influence the water quality within the domestic drinking water system. The focus of this research will be on the drinking water temperature and residence time in the domestic drinking water system.

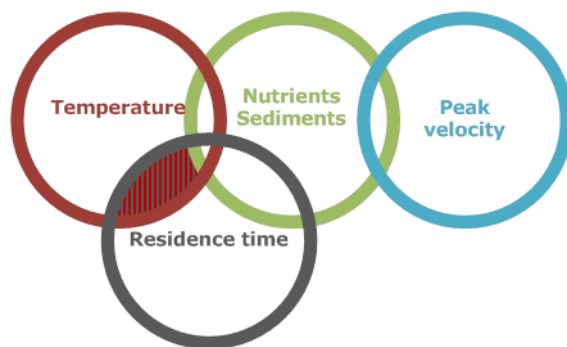


Figure 1.1.1 Four major parameters which influence water quality. The intersection of temperature and residence time is marked as red-grey.

1.1 Available data and research on domestic drinking water temperature

Available research on drinking water temperature within domestic drinking water systems was only found from a few authors (Völker, Schreiber et al. 2010). Most research on water quality in domestic drinking water systems is performed on temperature related subjects e.g. bacteria growth. Past research found on the intersection of drinking water temperature and residence time can be divided in three main subjects:

- heating of cold water through interference between hot and cold water systems (hotspots) or other heat sources;
- occurrence of *Legionella* in domestic drinking water system;
- stagnant water which has an influence on microbial growth and leaching of metals.

The focus on *Legionella Pneumophila* was triggered by the outbreak at Bovenkarspel in 1999. After this outbreak 32 people died because of an infection by *Legionella Pneumophila*. On behalf of Uneto-VNI and ISSO the research institute TNO developed a simple model to calculate the need for insulation inside a pipe shaft with cold and heat water pipes; the so called "Hotspotsim" (van Wolferen 2002). However, this model simulates a stationary situation where heat is transferred from hot to cold water systems and hence is only valid during night when no flow occurs in the cold water system. It is not valid during daytime

when heat is transferred through advection when there is a demand for (cold) water which creates flow. Research was performed on heating of drinking water due to district heating (van Wolferen 2007) and recommendations were given to prevent heating of drinking water pipes concealed in floors (van Wolferen 2008). However, the influence of consumer demand patterns was not included and hence a proper view on temperature fluctuations of drinking water over time is not investigated in former research.

1.2 Relevance for water companies and installation companies

Water companies are responsible for the water quality which comes from the tap (EU dir. 98/83/EG, Dutch drinking water decree (Dwb) art. 13), unless they can prove the owner has lacked the maintenance of his DDWS. Hence this is a case of a reversed burden of proof. Next to this, the customers may expect an active attitude from the water companies when it comes to knowledge about water quality. Quantitative knowledge about the water quality in domestic drinking water systems is therefore a necessity to provide counsel to the customer.

In contrast to legislation on drinking water in other EU countries the Dutch drinking water decree mentions a temperature threshold of 25°C at the tap. The presence of this threshold is probably related to the fact drinking water in the Netherlands is distributed without the use of chlorine. Several prescriptions for fitters/installers are based on the temperature threshold. One can think of the obligation to avoid heat influence of hot water pipes on cold water pipes. Such a point of heat interference between hot and cold water pipes is called a hotspot. However it is not proven if (and how) the influence at one or more hotspots in space and/or time influences the drinking water temperature at the tap. Next to this, the prevention focus is on the avoidance of temperatures above 25°C (VEWIN 2004, ISSO 2010, NEN 2011 [1]) and not on the problem behind: microbial activity.

1.3 Research questions

Since there is a lack of knowledge in domestic drinking water temperature dynamics, this research will be a first exploration in DDWS water quality dynamics. The research questions are:

1. How is the temperature related to water quality in DDWS?
2. How can the drinking water temperature in DDWS be modeled?

The first question creates the framework and basis for the second question; what is the relation between temperature and quality? This is a qualitative approach. The second question aims at the quantitative part; modeling will be used to determine the temperature behavior within the DDWS.

2 Problem description

Domestic drinking water systems exhibit several properties which can, if they interfere, create unwanted situations e.g. excessive bacterial growth. One can think of the presence of biofilms, which occurs at all surfaces in contact with water (Walker, Surman et al. 2000) combined with high residence times and high temperatures. There is however a lack of knowledge on the relation between residence time, temperatures and bacterial growth on the one hand, and the dynamics of consumer demand patterns on the other. Existing models do not incorporate the highly dynamic effect of consumer demands.

The second point of interest is formed by the temperature threshold mentioned in the Dutch legislation on drinking water which is currently on force. This threshold of 25°C, which has to be met at the tap, influences practical norms and standards. These norms form the basis of checklists and handbooks which are used in the design of domestic drinking water systems. Hence a lot of people have to deal (in)directly with this threshold. However, no evidence was found in the literature and from interviews to explain the choice for the temperature threshold of 25°C.

The subjects explained above emphasize the need for a proper DDWS model to determine the relation between patterns, infrastructure and water temperature at any point in time and space and to check whether the measures of avoiding hotspot are efficient.

3 Approach and methods

3.1 Introduction

The first research question was approached by both a literature study and modeling of temperatures and microbial activity. The answer of the second question is formed by the development of a heat transfer model for DDWS. The results of the literature study are partly reported in the annexes I *Brief introduction to water quality within the domestic infrastructure* and II *Legislation and standards in drinking water distribution*.

3.2 Temperature modeling

Measuring is often expensive and takes a lot of time. Modeling is therefore useful. By the use of an existing program which can perform hydraulic calculations it is possible to model the temperature dynamics in a DDWS. EPANET is chosen as hydraulic calculator. The Multi-Species Extension (MSX) package of EPANET is used to embed the temperature model described in this report. SIMDEUM is used to make a proper estimation of the tapping patterns. Hence three models are used to develop an infrastructure to model the temperature within DDWS as is shown in Figure 3.2.1.

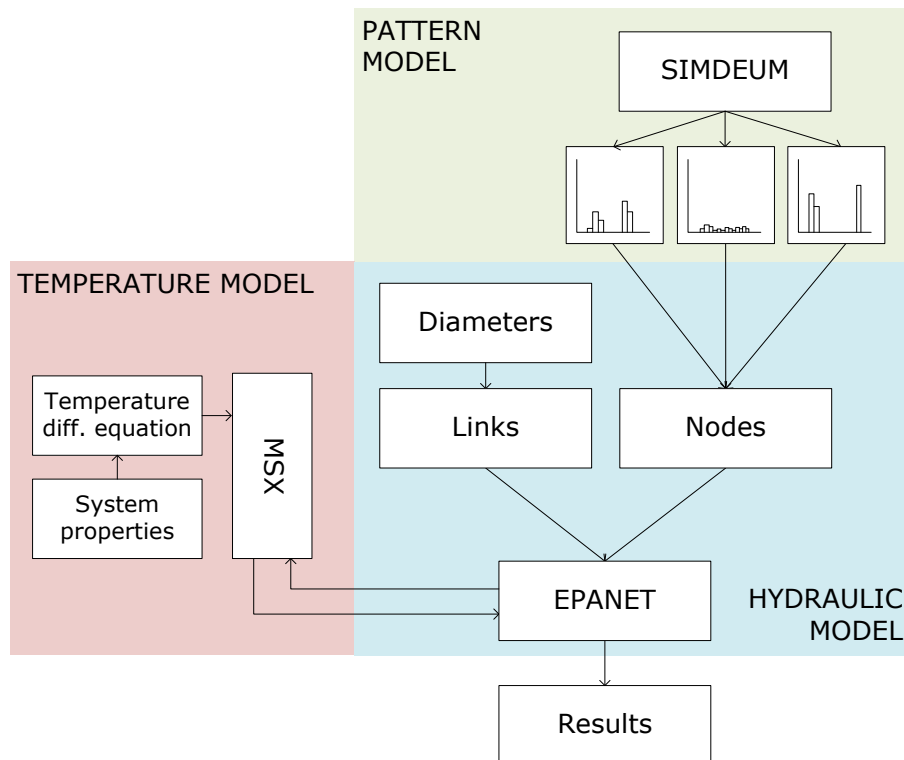


Figure 3.2.1 Scheme of different models which are used to obtain temperature data.

3.3 Introduction to domestic drinking water systems

There is a high variability in DDWS due to buildings' age, household sizes and types, appliances present and pipe materials being used.

Layout and trends in past and present

The design of a DDWS depends on several parameters. The ones which highly influence the layout are listed below.

- The type of housing: detached, semi-detached, terraced, apartment, etc. The type of house is the major parameter which determines the infrastructure length (mainly in horizontal perspective).
- The age of the DDWS which is related to the pipe materials being used.
- The type of house heating (condensing boiler, city heating, aquifer thermal energy storage (ATES)) which determines a lot about the infrastructure of heat water pipes.
- The national standards for DDWS: direct and indirect (use of reservoir) systems.

During the last 50 years, housing in The Netherlands experienced a lot of developments. The average domestic water equipment changed from an elementary combination of one toilet, one shower, a kitchen tap provided with a geyser and one washstand to a situation with at least two toilets, shower, washing machine, dishwasher and possibly a bathtub. In the table below, the trends of water appliances during the last 50 years are visualized.

Period	Domestic appliances and water infrastructure	
1955 - 1965		<p>⊘ = water meter WS = wash stand S = shower T = toilet KS + G = kitchen sink and geyser</p>
1965 - 1975		<p>WM = washing machine</p>
1975 - 1985		<p>CB = condensing boiler (Dutch: high efficiency boiler) WB = wash basin</p>
1985 - 1995		<p>BT = bath tub FT = frontage tap (outside)</p>
1995 - 2005		<p>DW = dishwasher B = small kitchen boiler: electrical or hot-fill (dotted line)</p>

Figure 3.3.1 Trends in appliances and network layout during the last 50 years (Scheffer 2012).

Current developments can be found in the fields of sustainability and the transfer from functionality to wellness. Examples of the former are heat exchangers and solar boilers; the use of comfort showers is an expression of the latter. In newly designed DDWS two other developments can be discerned: the design of “*Legionella* free buildings” and the use of district heating through e.g. aquifer thermal energy storage (ATES).

Analysis of housing types

The size and model of a house determines mainly the length of the DDWS. As one can see from Figure 3.3.2 the distribution of different house types did not differ much between 1998 and 2009. Due to the economic crises – which came through in 2008 and did vastly affect the construction sector – roughly the same values can be assumed for the current situation. The building age can also have influence on the existing infrastructure. It is however difficult to relate building age to infrastructure because of the uncertainty through possibly performed reconstructions.

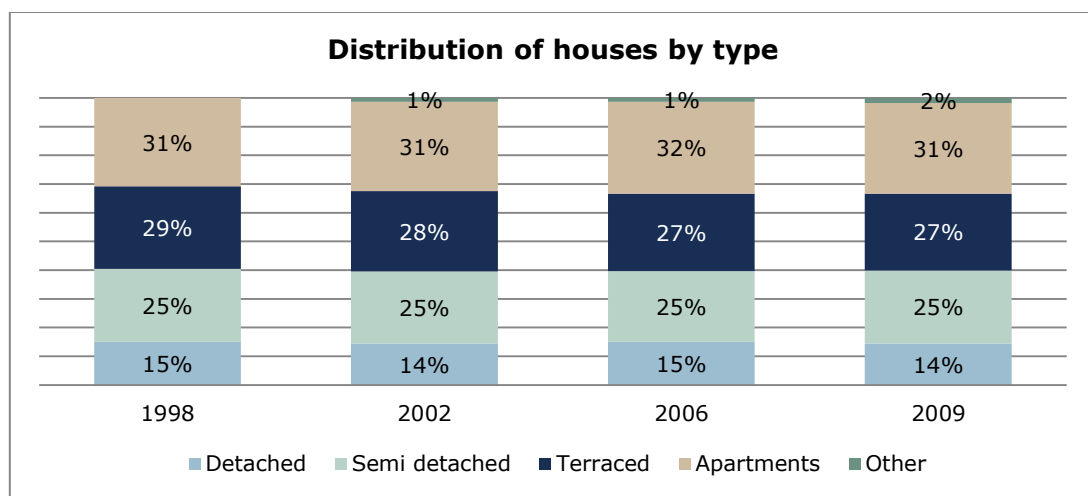


Figure 3.3.2 Distribution of different types of houses (CBS Statline).

Central heating and water heating systems

The heated water infrastructure highly depends on the devices and/or systems which are used to heat the water. Examples of such systems are:

- a. condensing boiler¹, used for both heating of drinking water and central heating;
- b. electrical or hot filled boiler at kitchen sink, used to heat water at the kitchen sink and to shorten hot water waiting times;
- c. district heating, used for central heating in houses;
- d. alternative forms of heating, e.g. the use of solar boilers, heat exchangers (energy recovery), heat pumps and aquifer thermal energy storage (ATES).

The penetration of condensing boilers within the Netherlands is estimated as >90% (CBS). Condensing boilers are often combined with smaller electrical or hot-filled boilers at the kitchen sink (see Figure 3.3.1) to reduce the waiting time for heat water which results in waste of water and energy.

District heating is used to heat houses with heated water which is heated centrally and transported through an underground piping system. These systems are mainly used when residual heat from e.g. a power plant is available. District heating is also used in

¹ The Dutch equivalent is called HR-ketel (high efficiency boiler).

combination with seasonal thermal energy storage in newly build districts. The amount of houses which is served by district heating in the Netherlands is around 4% (CBS). The penetration of alternative heating was less than 0.5% in 2011 (CBS, CBS 2012). When the distinct penetration numbers from above are combined it can be concluded that the vast majority of the Dutch households use a condensing boiler for house and water heating.

Pipe materials

Various materials are used in DDWS: copper, plastics, lead and stainless steel. Although there are other materials used, the focus will be on these materials because the large majority of DDWS consist of copper and plastics. Branch organization Uneto-VNI estimates an equal use of copper and plastics in new DDWS (Meerkerk 2013 [2]).

Copper

Copper is used since the thirties of the 20th century as material for DDWS to substitute lead pipes. Copper has several advantages:

- less biofilm forming on pipe wall compared to plastic pipes (Rogers, Dowsett et al. 1994, Lehtola, Miettinen et al. 2004, Oesterholt, Veenendaal et al. 2007);
- durable (Slaats 1996);
- less influence on aesthetic parameters compared to plastic pipes (Meerkerk and Slaats 2013);

Disadvantages can be found in the emission of copper ions and the possibility of oxidation. The former occurs due to stagnant water: it was estimated that 60% of the copper emission in wastewater sludge comes from copper drinking water pipes. The latter can occur due to installation faults, sediments or too high water velocities (Slaats 1996). The limitation of biomass growth on the inner wall of copper pipes is related to the effect of release of copper ions on micro organisms. It is suggested (Moritz, Flemming et al. 2010) that copper ions disturb the metabolic function, cause cell injury or induce a inactive state. The latter means bacteria are in a very low metabolic state and do not reproduce.

Plastics

Since the nineties the plastics are more and more used in DDWS. Plastics are more favorable compared to copper for the following reasons (Slaats 1996):

- no copper emission to the environment;
- plastics are easier to install;

Types of plastics which are currently used are PVC-C (Chlorinated Polyvinylchloride), PE-X (Crosslinked Polyethylene), PE-RT (Polyethylene-resistant temperature), PB (Polybutene) and PP-R (Random copolymerized Polypropene) (Slaats 1996, Meerkerk and Slaats 2013). The leaching of biodegradable compounds (plasticizers, antioxidants, lubricants and heat stabilizers) by plastics - providing nutrients to biofilms - is a disadvantage of these materials (Moritz, Flemming et al. 2010). Next to this the uncertainty of durability is higher compared to copper pipes.

Other materials

Other materials which are used in DDWS are lead and stainless steel. Stainless steel is hardly used for DDWS in the Netherlands (Meerkerk and Slaats 2013) but is more common in other countries. Although it is prohibited to use lead as material for drinking water pipes, lead pipes can still be found in old buildings. It is assumed that only a few percent of the DDWS consist of lead (Meerkerk and Slaats 2013).

3.4 Consequences of temperature increase

Negative influences of temperature increase can be found in the microbial activity, the leaching of metals² and the deterioration of taste when water is used for drinking. The temperature is of high influence on the activity of micro organisms. When water is heated the number of bacteria (heterotrophic plate count or HPC) can exceed the threshold of 100 cfu/100 ml mentioned in the Drinking water Decree, especially when the water is stagnant. A combination of long residence times and higher temperatures (especially above 30°C) give the opportunity to the accumulation of micro organisms which are present in the DDWS. Next to this higher water temperatures can cause lead release from brass fittings (Sarver and Edwards 2011). Temperature gradients stimulate the effect of copper release from copper pipes (Rushing and Edwards 2004).

Drinking water which is heated could be unwanted if the DDWS user draws water from the tap for consumption. It is likely the user will flush this heated water away before he starts consuming. This flushing behavior depends on:

- user demand pattern which determines the residence time;
- temperature of the water at the tap;
- personal preference.

The effect of this flushing behavior on the temperature in the DDWS will be investigated during this research.

3.5 Modeling temperature in domestic drinking water systems

To model the drinking water temperature within the DDWS there is need for a realistic DDWS network and a demand pattern. These are obtained using former research and models from KWR.

EPANET hydraulic model and SIMDEUM demand modeling

The open source program EPANET is used to perform hydraulic calculations. EPANET is available for free on the site of the US Environmental Protection Agency (EPA). Demands were modeled using SIMDEUM (SIMulation of water DEMand, and End Use Model), a demand pattern model developed at KWR in Nieuwegein (Blokker 2010). For sake of clear comparison only one SIMDEUM pattern was used to test the model in an EPANET environment. The total flow of this pattern is shown in Figure 3.5.1. This pattern belongs to a small household consisting of 2 persons. Because there are demands visible during the whole day from 8.00 AM to 12.00 PM it is very likely this pattern belongs to a household of retired persons.

² These subjects are further explained in Annex I *Brief introduction on water quality within the domestic drinking water system.*

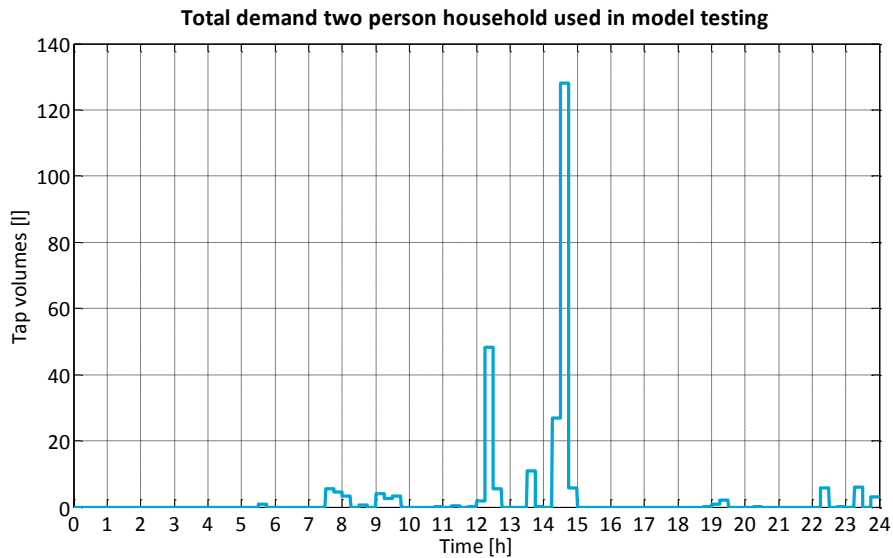


Figure 3.5.1 Tap volumes of pattern which was used to test the heat transfer model in MSX. The cumulative time step equals 15 minutes (90 time steps in MSX model).

Modeled DDWS types

The heat transfer model explained in chapter 3.6 was tested in EPANET MSX on three different networks. The basic network, which represents a simple DDWS, is shown in Figure 3.5.2. This network was obtained from former research on domestic drinking water systems (Poznakovs 2012). A detailed figure of this network containing pipe diameters and lengths can be found in Annex III.

#	Group	Tap points
1	Water meter	N.A.
2	Ground floor toilet	Toilet, wash basin
3	Kitchen	Kitchen tap (C,H) Dishwasher
4	1 st floor toilet	Toilet
5	Bathroom	Shower (C,H) Wash stand (C,H)
6	3 rd floor	Washing machine Central heater (at check valve)

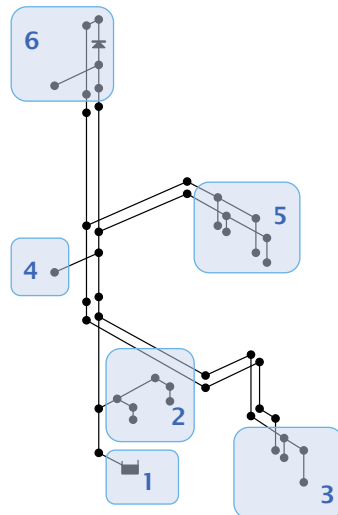


Figure 3.5.2 Basic EPANET DDWS model.

Next to this an extended version of this network was developed, where horizontal pipes are ten times longer compared to the reference case. This simple method gives insight in differences between several types of houses (detached, semi-detached, etc.). At last an apartment building was simulated (Figure 3.5.3). The Centrumplan IJsselmonde (Rijneveld 2012) was used as an example. The water supply to the residential part of this building is divided in five stages which all have their own hydrophore. The network layout of the fifth stage, which consists of 72 households is horizontally projected. Hence an apartment building with number of housholds 12x6x1 is modeled. 18 different patterns were

distributed randomly in the network to create a more realistic flow pattern in the collective supply lines. The apartment of interest is modeled like the reference case (see Figure 3.5.3; upper right corner). Hence the apartment of interest is situated in the worst position which is inherent to the longest supply line to the DWDS. A detailed figure of the network shown in Figure 3.5.3 containing pipe diameters and lengths can be found in Annex III.

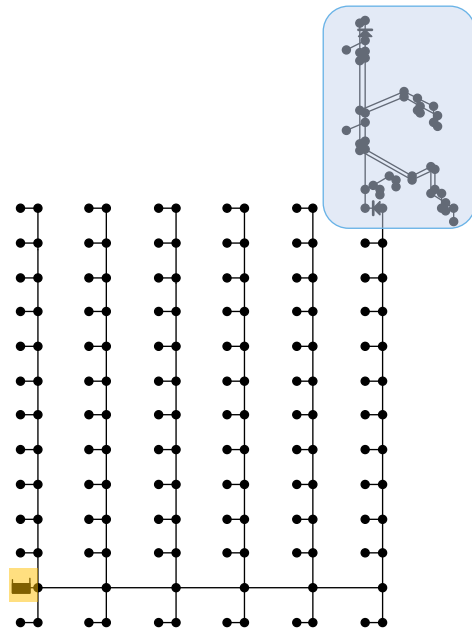


Figure 3.5.3 Network layout apartment building with apartment of interest in the marked field; the supply point is marked yellow.

Modeled scenarios

Six different scenarios were used to obtain results from the temperature behavior within the domestic drinking water system. A reference case is used to perform a convenient comparison. All scenarios are listed in Table 3.5.1.

Table 3.5.1 Scenarios which are simulated using the DDWT model.

Scenario	Specification
Reference case	Case which is used to compare with all scenarios. Environmental temperature equals 18°C and water temperature at the boundary (inflow point) equals 5°C.
Summer	Environment temperature is set 28°C and the water temperature at the inflow point equals 18°C.
Different network layouts	In this scenario different network layouts are compared which are shown in Figure 3.5.2 and Figure 3.5.3 and explained in the text above.
Distinct pipe environments	In this scenario some pipes are modeled to be concealed by walls.
Pipe shaft heating	In this scenario a group of pipes is exposed to an environment temperature of 35°C.
Small hotspots at different locations	In this scenario small hotspots are modeled at three different places. At the hotspot location the environmental temperature equals 35°C.
Different tap volumes	To investigate the influence of the tap volume on the water temperature the demand volumes from the reference case were divided and multiplied by a factor two.

3.6 Heat transfer model

The main goal of this paragraph is to clarify the complexity of the real situation and how this complexity can be transferred to a model by elimination of non-significant processes. The heat transfer model which is described in this chapter is embedded afterwards in the EPANET MSX modeling environment.

Influences on water temperature

The water temperature at a certain point in time and space is influenced by many parameters. The most important ones are listed in Figure 3.6.1.

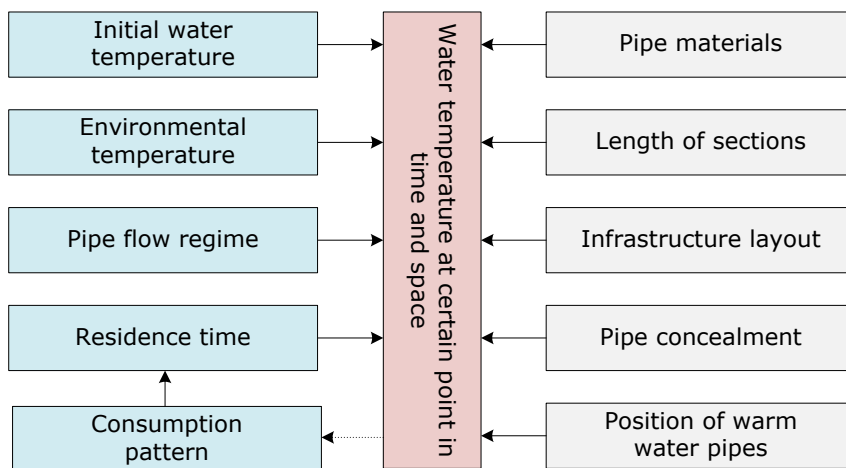


Figure 3.6.1 Most important influences on water temperature within DDWS.

The model is able to take all these influences into account. The possible influence of temperature on the consumption volume (explained in paragraph 3.4) is neglected in the calculations. However, the changing tap volumes scenario (Table 3.5.1) is used to quantify the effects of flushing behavior on the drinking water temperature in the DDWS. The model uses a lagrangian approach. This means the model tracks changes in discrete parcels of water which move through the system (Shang and Uber 2011).

Temperature-time relation

Since the temperature changes by time there is need for a temperature-time relation which describes the temperature change over time. Therefore we first analyze the processes in a control volume with arbitrary length Δx in Figure 3.6.2.

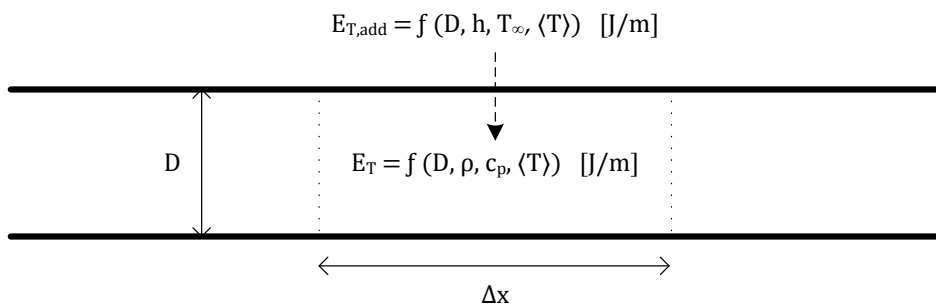


Figure 3.6.2 Control volume with arbitrary length Δx .

For small Δx the control volume can be considered as a lumped system. This means that the temperature gradient (∇T) within the section is zero. This assumption holds because the

diameters are relatively small (up to 31 mm). The temperature is therefore denoted as $\langle T \rangle$, which means the average temperature over the pipe diameter. A thermal energy balance over the control volume with arbitrary length Δx during Δt yields:

$$E_{T,t+\Delta t} - E_{T,t} = E_{T,add} \quad [1.1]$$

where $E_{T,add}$ is the thermal energy added to the system during Δt . Elaboration of eq. 2.1 gives:

$$\frac{\pi}{4} D^2 \rho c_p \langle T \rangle_{t+\Delta t} - \frac{\pi}{4} D^2 \rho c_p \langle T \rangle_t = \pi D h (T_\infty - \langle T \rangle_t) \Delta t \quad [1.2]$$

where h is the heat transfer coefficient in $W/(m^2 \cdot K)$ which incorporates both conduction and convection processes, T_∞ the environmental temperature, $\langle T \rangle$ the average temperature in the control volume and c_p the heat capacity of the water. Eq. 1.2 can be rewritten as:

$$\frac{\langle T \rangle_{t+\Delta t} - \langle T \rangle_t}{\Delta t} = \frac{4h}{\rho c_p D} (T_\infty - \langle T \rangle_t) \quad [1.3]$$

Taking the limit $\Delta t \rightarrow 0$ in eq. 2.3 results in:

$$\frac{d\langle T \rangle}{dt} = \frac{4h}{\rho c_p D} (T_\infty - \langle T \rangle) \quad [1.4]$$

This differential equation describes the temperature change within one small section which moves through the DDWS. The change of temperature by time (dT/dt) is driven by the temperature difference ($T_\infty - T$). The denominator product of $\rho c_p D$ forms the capacity to absorb heat per unit area per degree temperature difference. The nominator is formed by h , the heat transfer coefficient. This parameter incorporates the different heat transfer processes which determine how the water in the control volume is heated during a certain time step Δt . Solving the differential equation with boundary condition $\langle T \rangle_{t=0} = T_0$ yields:

$$\ln \left(\frac{T_\infty - \langle T \rangle}{T_\infty - T_0} \right) = - \frac{4h}{\rho c_p D} t \quad [1.5]$$

Similar equations can be found in the literature (Çengel 2003, van den Akker and Mudde 2003).

The thermal resistance concept

In this paragraph the determination of the heat transfer coefficient h is explained. The heat transfer coefficient represents several heat transfer processes in- and outside the control volume. Analog to electrical circuits the different heat transfer processes can be seen as thermal resistances which can be added together (Çengel 2003).

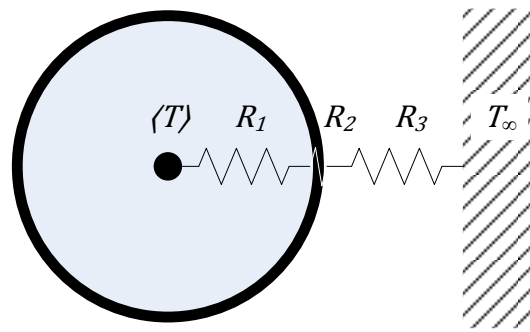


Figure 3.6.3 Thermal resistance concept.

This is shown in Figure 3.6.3 where R_1 equals the thermal resistance inside the pipe which depends on the flow conditions, R_2 equals the pipe wall thermal resistance and R_3 represents the outside thermal resistance. Analog to electrical circuits problems the resistances can be added together depending on how they are connected. Since the resistances from Figure 3.6.3 are in series, the

$$R_{comb} = \frac{1}{R_1 + R_2 + R_3} \quad [2.1]$$

or:

$$h_{comb} = \frac{1}{1/h_{water} + 1/h_{pipe} + 1/h_{out}} \quad [2.2]$$

As mentioned earlier h_{out} depends on the environment of the pipe h_{pipe} depends on the wall thickness and pipe material and h_{water} depends on the fluid conditions.

Conductive heat transfer

Conduction is the transfer of heat through a solid since the molecules cannot move freely. Conduction appears in three ways:

- conduction through the pipe wall which separates the fluid from the environment outside the pipe;
- conduction through the motionless fluid (if $v = 0$);
- conduction through the boundary layer on the pipe wall (if $v > 0$).

The heat flux through conduction can be described by:

$$\dot{q}_{cond} = \lambda \frac{\Delta T}{D} \quad [3]$$

where \dot{q} is the heat flux in W/m^2 , λ the thermal conductivity in $W/(m \cdot K)$ and ΔT the difference in temperature over the medium and D the diameter of the pipe. The heat transfer coefficient of the heat conduction through the pipe wall can be described by:

$$h_p = \frac{\lambda_p}{d} \quad [4]$$

where λ_p is the thermal conductivity of the pipe wall in $W/(m \cdot K)$ and d is the pipe wall thickness.

Under conditions of motionless fluid, the heat transfer from outer pipe wall to bulk water will occur through conduction. In this case the heat transfer coefficient is constant and the Nusselt number equals 5.8 (van den Akker and Mudde 2003). The heat transfer coefficient for motionless flow is therefore equal to:

$$h_{in} = \frac{5.8 \lambda_w}{D} \quad [5]$$

Concealment of pipes is used for several reasons:

- The passage of a floor section (e.g. when a pipe enters the ground floor coming from the crawlspace)
- For sake of aesthetics: the concealment of water pipes in walls (e.g. bathrooms and kitchens).

In both situations there is a small layer of air between the wall material (building material, e.g. concrete) and the outer pipe wall. The heat capacity of the small air layer around concealed pipes has a very small heat capacity compared to the heat capacity of the water in the pipe. The latter is approximately a factor 10^4 higher than the former. The temperature influence of the air layer is therefore neglected. Hence the air layer can be modeled as a simple thermal resistance. h_{out} therefore determined by:

$$h_{out} = \frac{\lambda_a}{\delta_a} \quad [6]$$

where δ_a equals the thickness of the motionless air layer.

Convective heat transfer

The heat transfer through fluid motion is called convection. Convection is denoted as “free” when it is driven by the buoyancy force. In DDWS convection occurs when:

- the water in the boundary layer is heated and natural convection occurs through the buoyancy force which is driven by density differences (if $v = 0$);
- the motion of the bulk water creates forced convection (if $v > 0$).
- heat is transferred from or to the outer pipe wall from pipes which are surrounded by air which can move freely by convective processes.

Nusselt number for water flow

Heat transfer through convection can be described by (Çengel 2003):

$$\dot{q}_{conv} = h\Delta T \quad [7]$$

Where h is the heat transfer coefficient in $W/(m^2 \cdot K)$. This parameter represents all processes which occur during heat transfer between a solid surface and a fluid. Or: the rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference. This includes both convection (due to the fluid motion) and conduction (due to the motionless boundary layer, where $v_s = 0$ due to the shear stress). Since a lot of heat and mass transfer phenomena occur during convection between a solid and a motion fluid the convection heat transfer coefficient depends on a huge number of variables. In order to reduce the total number of variables, dimensionless numbers are commonly used in heat transfer analysis. The most common one is the Nusselt number which expresses the ratio of total heat transfer to heat transfer through conduction:

$$\text{Nu}_w = \frac{\text{heat transfer through convection}}{\text{heat transfer through conduction}} = \frac{\dot{q}_{\text{conv}}}{\dot{q}_{\text{cond}}} = \frac{h\Delta T}{\lambda_w \Delta T / D} = \frac{Dh}{\lambda_w} \quad [8.1]$$

in which D is the pipe diameter in m and λ_w the thermal conductivity of the fluid in $\text{W}/(\text{m}\cdot\text{K})$. The other dimensionless numbers which play a role in forced convection inside water flowing through a pipe are the Reynolds, Prandtl and Graetz numbers and the so called viscous group (Vi). The Nusselt number is a function of the other numbers (van den Akker and Mudde 2003):

$$\text{Nu} = f(\text{Re}, \text{Pr}, \text{Gz}, \text{Vi}) \quad [8.2]$$

Under turbulent flow conditions the proportion of the Graetz and Grashof numbers can be neglected since the natural convection (Grashof) and the conduction perpendicular on the flow direction (Graetz) phenomena are disturbed by the vortexes of the turbulent flow. The contribution of Vi can also be neglected since the turbulent flow will cause a mixing of less and more viscous particles.

$$\text{Nu} = f(\text{Re}, \text{Pr}) \quad [8.3]$$

The Gnielinski equation is used to calculate the Nusselt number in turbulent flow conditions. The Gnielinski equation is a modification of the second Petukhov equation by making it valid for lower Reynolds numbers (Çengel 2003):

$$\text{Nu}_w = \frac{(f/8) (\text{Re} - 1000) \text{Pr}}{1 + 12.7 (f/8)^{0.5} (\text{Pr}^{2/3} - 1)} \quad \left(\begin{array}{l} 0.5 \leq \text{Pr} \leq 2000 \\ 3000 < \text{Re} < 5 \cdot 10^6 \end{array} \right) \quad [9]$$

where f is the friction factor. The entrance regions where the flow is not fully developed is typically short for turbulent cases (magnitude $10D$) and thus the Nusselt number determined for fully developed turbulent flow can be used approximately for the entire tube. To investigate the occurrence of laminar flow, the thermal entrance lengths for different pipe diameters are estimated using the following approximation (Çengel 2003):

$$L_{e,therm} \cong 0.05 \text{ Re Pr } D \quad [10]$$

for commonly used pipe diameters for copper pipes at a temperature of 10°C :

D [mm]	Re = 500	Re = 1000	Re = 2300
10	2.36	4.73	10.87
13	3.07	6.14	14.13
19.8	4.68	9.36	21.52

Since $L_{e,therm}$ is very large compared to the occurring pipe lengths in DDWS it is assumed only *undeveloped* laminar flow occurs from which the Nusselt number can be described by (Çengel 2003):

$$\text{Nu}_w = 3.66 + \frac{0.065(D/L)\text{Re Pr}}{1 + 0.04[(D/L)\text{Re Pr}]^{2/3}} \quad [11]$$

Since only undeveloped laminar flow occurs, the influence of boundary layers can be neglected. Although the boundary of $\text{Re} = 2300$ is discussable, it is assumed that fluid motion with Re numbers above 2300 is more turbulent than laminar and hence described by the Gnielinski equation. The complete function to determine the Nusselt number for fluid motion equals therefore:

$$\text{Nu}_w = \left\{ \begin{array}{l} \text{Re} < 10: \quad 5.8 \\ 10 < \text{Re} \leq 2300: \quad \left(3.66 + \frac{0.065(D/L)\text{Re Pr}}{1 + 0.04[(D/L)\text{Re Pr}]^{2/3}} \right) \\ \text{Re} > 2300: \quad \left(\frac{(f/8)(\text{Re} - 1000)\text{Pr}}{1 + 12.7 (f/8)^{0.5} (\text{Pr}^{2/3} - 1)} \right) \end{array} \right\} \quad [12]$$

Nusselt number for air flow

Natural convection occurs around pipes which are not concealed by walls. Under a temperature gradient (ΔT) heat from the surrounding air is transferred into the pipe material, or the other way around, depending on the sign of the gradient. The transfer of heat from the surrounding air to the outer pipe wall will take place through conduction – in the air boundary layer around the pipe – and convection. Convection will happen due to buoyancy forces which occur because of temperature differences in the boundary air layer around the pipe. It is assumed no forced convection occurs since there is no external driving force to create forced convection. Natural convection is generally described by the product of the Grashof and Prandtl numbers, which yields the Rayleigh number:

$$\text{Nu}_a = \alpha(\text{Gr} \cdot \text{Pr})^\beta = \alpha \text{Ra}^\beta \quad [13]$$

where α and β are coefficients which are experimentally determined. The Grashof number can be determined by:

$$\text{Gr} = \frac{g\beta(T_\infty - T_s)D^3}{\nu^2} \quad [14]$$

where g is the gravity acceleration (9.81 m/s^2), T_s the temperature at the surface of the outer pipe wall and ν the kinematic viscosity. β is the expansion coefficient in K^{-1} . Since the air flow around pipes develops while flowing, Nusselt numbers which are averaged along the geometries should be used, which can be found in the literature (Çengel 2003). For *horizontal* pipes the Nusselt number for natural convection equals:

$$\text{Nu}_a = \left(0.6 + \frac{0.387\text{Ra}^{1/6}}{[1 + (0.559/\text{Pr})^{9/16}]^{8/27}} \right)^2 \quad [15]$$

The Nusselt number for natural convection around *vertical* pipes equals:

$$\text{Nu}_a = 0.59 \text{Ra}^{1/4} \quad [16]$$

From the formulae above the heat transfer coefficient for the heat transfer from air to pipe can be derived using:

$$h_{out} = \frac{\text{Nu}_a \lambda_a}{D} \quad [17]$$

for pipes which are not concealed by walls.

Heat transfer through radiation

Since both concealed and free pipes are surrounded by air, heat is also transferred from ($T > T_\infty$) and to ($T_\infty > T$) the pipe through radiation. The heat transfer coefficient for radiation is described by (Çengel 2003):

$$h_{rad} = \epsilon\sigma(T_s^2 + T_w^2)(T_s + T_w) \tag{18}$$

where T_s and T_w are in Kelvin. T_w is the temperature of the surrounding walls which emit thermal radiation, ϵ is the emissivity of the material and σ the Stefan-Boltzman constant. When heat is transferred from the environment to an object the absorption α can substituted for ϵ . Both are dimensionless ratio's between 0 and 1. The determination of α is debatable since it depends a lot on the rate of corrosion which highly influences the absorption ratio of copper pipes. Figure 3.6.4 shows the result of modeling with and without accounting the thermal radiation. Since the contribution of the thermal radiation is small and the definition of h_{rad} depends on uncertain assumptions (temperature of surrounding walls and absorption ratio) the thermal radiation was left out in the calculations.

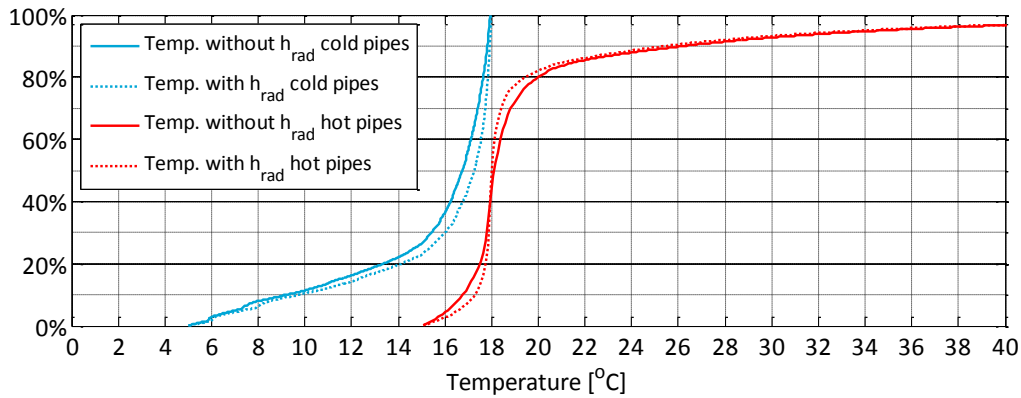


Figure 3.6.4 Temperatures which occur in the model with and without accounting for thermal radiation.

Hotspot accounting

Hotspots occur where air around pipes is heated by the heated water in the pipes. This heated air can influence the drinking water temperature in cold water pipes. This effect is incorporated in the model by changing the environment temperature T_∞ for pipes which are influenced by surrounding hot air. The dynamic influence of ordinary heat water pipes is not incorporated in the model yet because of shortcomings in EPANET MSX (see Annex IV).

Summary thermal resistances

The mathematical descriptions of h_{water} , h_{pipe} and $h_{outside}$ in the previous paragraphs were gathered in Table 3.6.1 below.

Table 3.6.1 Expressions for h_{comb} under different flow and pipe environment conditions.

	Concealed pipes	Free pipes
Fluid motion	$\frac{1}{\frac{D}{Nu_w \lambda_w} + \frac{d}{\lambda_p} + \frac{\delta_a}{\lambda_a}}$	$\frac{1}{\frac{D}{Nu_w \lambda_w} + \frac{d}{\lambda_p} + \frac{D}{Nu_a \lambda_a}}$
No visible fluid motion	$\frac{1}{\frac{D}{Nu_{w,v=0} \lambda_w} + \frac{d}{\lambda_p} + \frac{\delta_a}{\lambda_a}}$	$\frac{1}{\frac{D}{Nu_{w,v=0} \lambda_w} + \frac{d}{\lambda_p} + \frac{D}{Nu_a \lambda_a}}$

In MSX both the term for concealed and free pipes are incorporated in the formula which determines h to make the equation valid for every situation. Hence the term for concealed pipes should be zero at free pipes and vice versa.

Table 3.6.2 Parameter values to make MSX model valid for both free and concealed pipes.

Parameter	Free pipes	Concealed pipes
d	0	$\neq 0$
Nu	$\neq 0$	0

Model simplifications

Several expressions from paragraph 3.6 can be simplified while keeping the accuracy of the model within acceptable margins. These simplifications were modeled and the deviation from the initial model was monitored for each simplification. The result is shown in Table 3.6.3.

Table 3.6.3 Simplifications applied in mathematical description of model.

Simplification	Replacement formula	Relative error
$Gz > 0.1$ for laminar flow $Re > 10^4$ for turbulent flow	For forced convection within laminar and turbulent flow: $Nu_w = \begin{cases} Re < 10: & 5.8 \\ 10 < Re \leq 2300: & 3.66 \\ Re > 2300: & 0.023 Re^{0.8} Pr^{1/3} \end{cases}$	< 0.001
Both horizontal and vertical pipes treated as vertical plates	$Nu_a = 0.59 Ra^{1/4}$ Characteristic length is D for horizontal pipe and L for vertical pipe	< 0.05

MSX water quality modeling

The Multi-Species Extension of EPANET was used to embed the mathematical descriptions of paragraph 3.6 and to model the temperature change within the network shown in Figure 3.5.2. Although EPANET MSX was designed for chemical and/or biological species decay modeling other applications are possible (Blokker and Pieterse-Quirijns 2013). Therefore eq. 1.5 and several thermal resistance equations (see Table 3.6.1) are embedded in EPANET MSX. The exact .msx file which was used can be found in annex IV.

Temperature as surrogate parameter for microbial activity

From the literature study on water quality in DDWS (see Annex I) it is concluded the largest effects of temperature increase in drinking water can be found in microbial activity. Although temperature is only one parameter which influences microbial activity it is one of the major drivers since the other parameters are often not limiting factors. The relation between temperature and the growth of micro organisms can be approached using (Blokker and Pieterse-Quirijns 2012):

$$\frac{dN}{dt} = M(T) \cdot N \quad \text{with} \quad M(T) = M_{opt} \cdot e^{\frac{(T-T_{opt})^2}{0.2(T_{min}-T_{opt})^2}} \quad [19]$$

where N is the number of micro organisms, $M(T)$ the growth at a certain temperature in s^{-1} , M_{opt} the growth at the optimal temperature, T_{opt} the optimal growth temperature and T_{min} the minimal growth temperature. Two types of micro organisms are used to compare several

scenario's where the temperature rises above the threshold of 25°C. One having a high optimal growth temperature (type I) and the other having a low optimal growth temperature (type II) These are listed in the table below.

Table 3.6.4 Growth parameters for two well-known micro organisms (Blokker and Pieterse-Quirijns 2012).

Parameter	Description	Unit	Type I	Type II
M_{opt}	optimal growth rate	s^{-1}	$1.15 \cdot 10^{-5}$	$2.75 \cdot 10^{-5}$
T_{opt}	optimal growth temperature	°C	37	25
T_{min}	minimal growth temperature	°C	15	5

The concentration of 250 cfu/l was chosen as a boundary condition at the inflow node.

Assumptions

Since every DDWS is different some assumptions have to be made. Some are based on the literature, others are the result of a heuristic approach. They are listed in Table 3.6.5 together with their justification.

Table 3.6.5 Assumptions in modeling the DDWT.

Parameter	MSX id	Value	Justification
Environment temperature	T_env	18°C (reference case) 28°C (summer case)	Heuristic approach. Value must be acceptable for the whole network and is therefore chosen to be 2 degrees lower than the standard room temperature of 20°C.
Inflow water temperature	TEMP	5°C (reference case) 18°C (summer case)	Based on the literature Blokker and Pieterse-Quirijns 2013.
Water temperature after passing the heater	TEMP	55°C	Based on NEN 2011 [2].
Hotspot temperature	T_env	35°C	Heuristic approach assuming hot water pipes in the cold pipe environment. It is assumed hot pipes contain water at a temperature of 40-50°C.
Number of micro organisms after passing heater	numMO	0	Heuristic approach based on norms. All bacteria should be killed after heater passage if heater is well adjusted.
Inflow number of micro organisms	numMO	250 cfu/l	Heuristic approach. During simulation the focus will be on micro organism <i>growth</i> . Hence the boundary condition for the number of micro organisms is less important and the focus in the results will be on the <i>growth index</i> .
Pipe material (copper)	lambda_p	403 W/(m · K)	Heuristic approach; it is assumed one material was used for the whole network (Meerkerk 2013 [2]).

Since it is impossible in MSX to couple a variable pattern (e.g. dynamic environmental temperature) to a parameter the environmental temperature is assumed to be constant (see also Annex IV).

Water properties are all obtained from the literature (Janssen and Warmoeskerken 1991) at a temperature of 20°C and can be found in Annex IV. They are assumed to be constant within the relevant temperature range (0-55°C).

4 Results

4.1 Explanation of used graphs

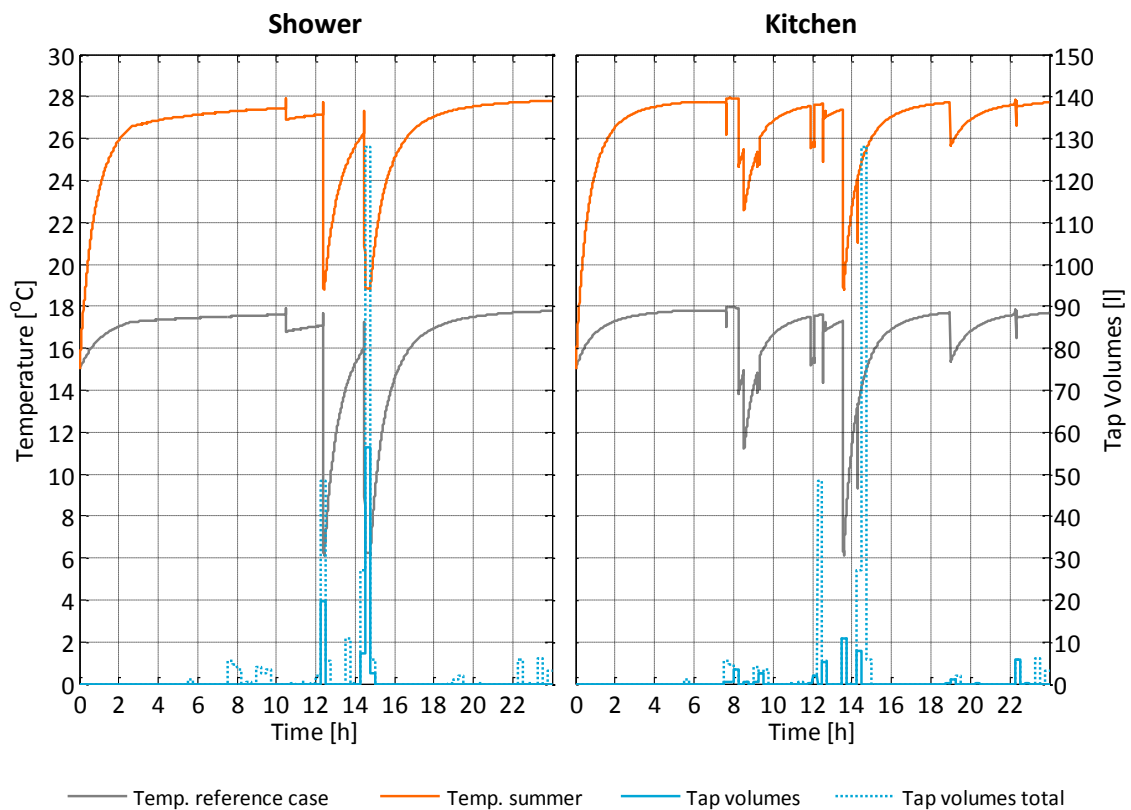
For every calculated scenario at least three graphs are shown:

- For every scenario the drinking water temperature at kitchen and shower tap is plotted. Physical contact of persons with water will mostly occur at these tap points. This also applies to the bathroom washstand and the toilet washbasin. The results for these tap points are shown in Annex III. The total demand volume in the system and the local demand volume at the tap are shown next to the temperature.
- One cumulative frequency graph for the temperatures of cold (blue) and hot (red) pipes at every time step for all pipes.
- For scenarios where the drinking water temperature exceeds the threshold of 25°C the results for microbial growth are shown in a third figure.

For sake of clarity the residence time is not shown in the figures since it linearly correlated to the temperature.

4.2 Reference case vs. summer day

For a summer scenario the initial conditions mentioned in paragraph 3.6 were used. The result is shown in Figure 4.2.1.



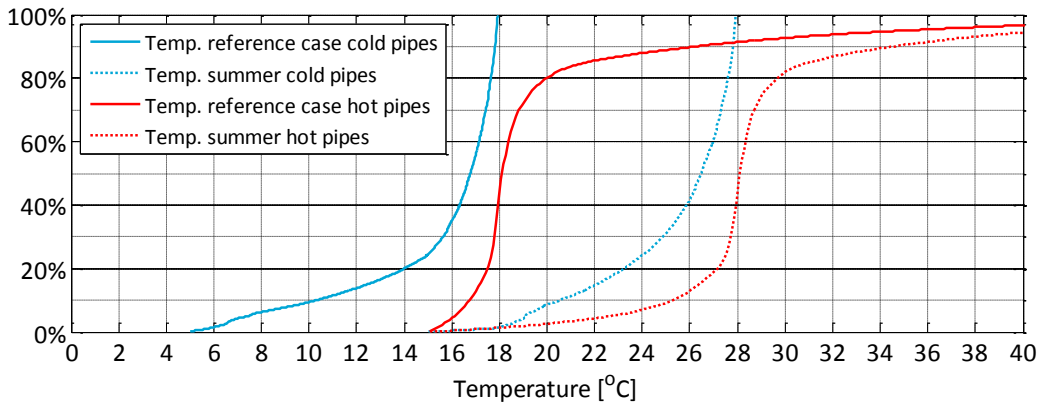


Figure 4.2.1 Results summer scenario compared to reference scenario.

Although the environmental temperature is 10°C higher compared to the reference case the DDWS temperature behavior is the same in both situations; the environment temperature is almost reached after 4 hours. This underlines the influence of the environmental temperature. Hence there are no striking differences between the reference case and the summer case. The temperature curves undergo a translation of 10°C. This has effects on the growth of micro organisms as can be seen in Figure 4.2.2:

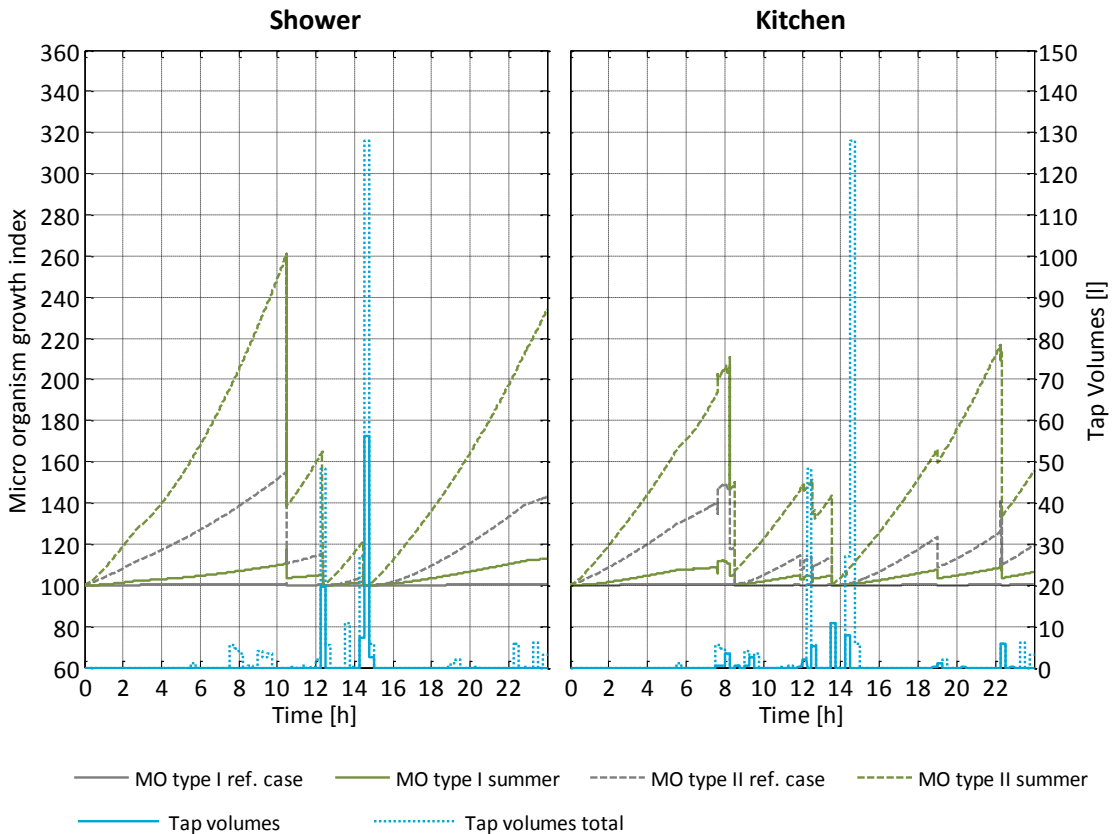


Figure 4.2.2 Influence of summer temperatures on bacterial growth of micro organisms (MO) type I and type II at shower and kitchen tap.

The environment temperature has visible impact on the bacterial growth of micro organisms with a lower optimal growth temperature (type II) since these show a maximal growth of 2.6

times the initial value after approximately 10 hours of stagnancy (Figure 4.2.2). The effect on micro organisms with lower optimal growth temperatures (type I) is less.

4.3 Different housing types

In Figure 4.3.1 the results for different housing types mentioned in paragraph 3.5 are shown.

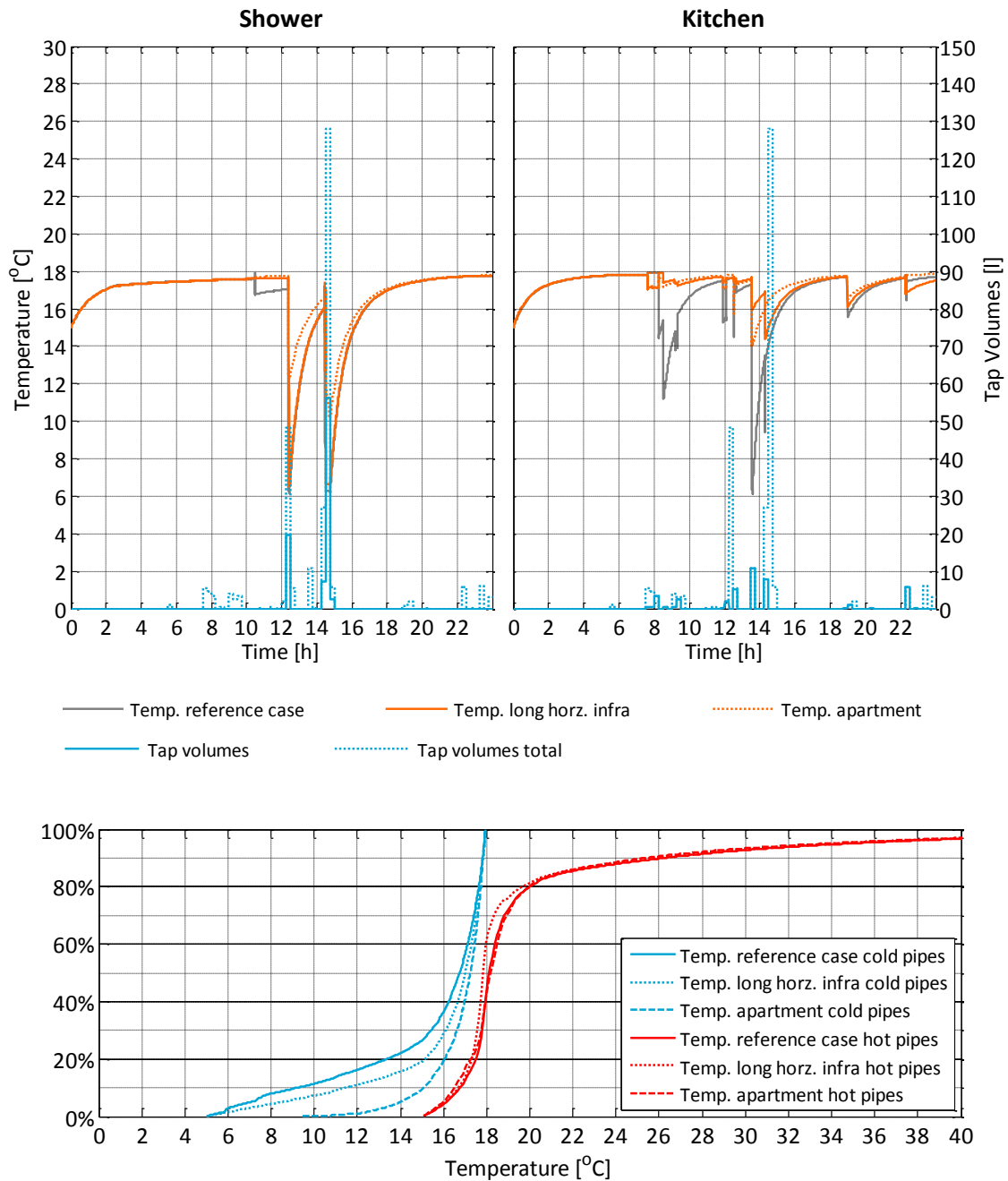


Figure 4.3.1 Results comparison three different types of houses.

For larger tap volumes (>20 l, shower graph) the three cases show only small differences. For smaller tap volumes (<20 l, kitchen graph) both the household with long horizontal pipes and the apartment case show higher temperatures. From these two the apartment building shows slightly higher temperatures at the kitchen and shower tap (Figure 4.3.1 a) and in the network pipes (Figure 4.3.1 b).

4.4 Effects pipe concealment

For the reference case it is assumed no pipe is concealed. To investigate the effects of concealed pipes one network layout was created where several pipes are concealed (Figure 4.4.1).

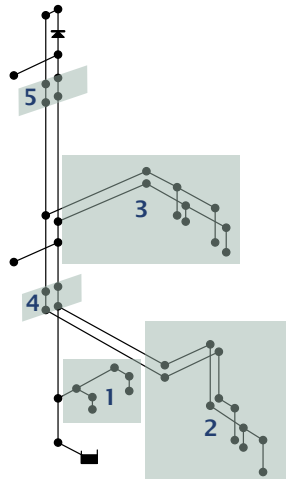
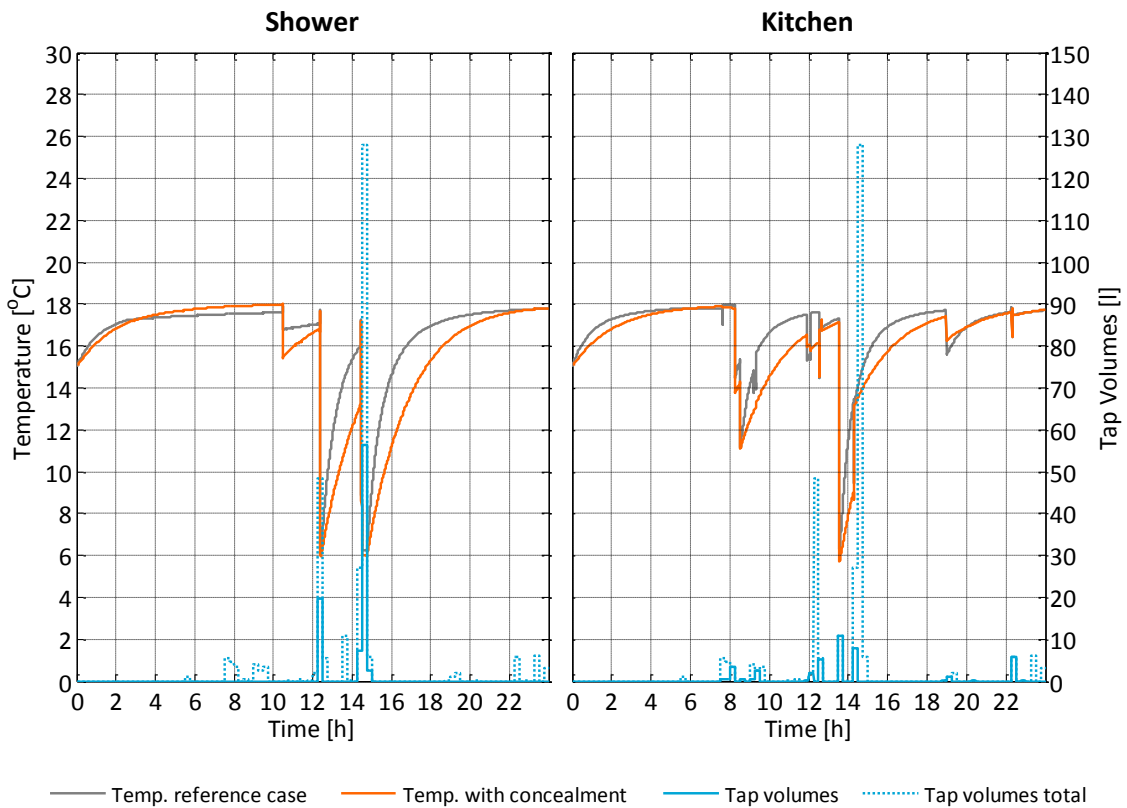


Figure 4.4.1 Basic model with concealed pipes. All pipes which are concealed are in the green zones:
 1. ground floor toilet group;
 2. kitchen group;
 3. shower group;
 4/5. floor passages.

The differences between reference case and case with pipe concealment are shown in Figure 4.4.2.



— Temp. reference case — Temp. with concealment — Tap volumes ··· Tap volumes total

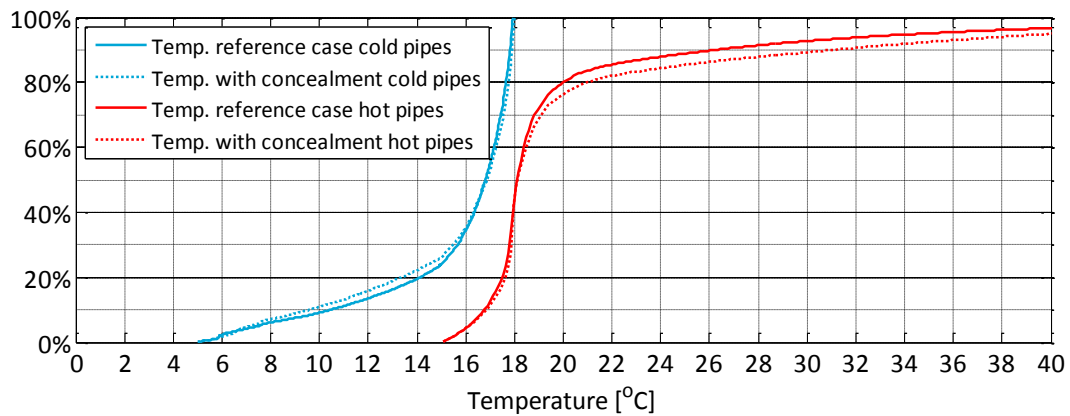


Figure 4.4.2 Results of reference case and pipe concealment case.

There are no major differences visible between both cases (Figure 4.4.2b). At the shower and kitchen tap the largest differences occur after a temperature decrease of more than 4°C. This can be explained by the temperature dependence of natural convection which takes place around free (not concealed) pipes. For concealed pipes this is not the case. Hence these are heated more slowly.

4.5 Hotspot simulation

In this paragraph the results for two types of hotspots are shown. At first the results for pipe shaft heating are shown. Afterwards the influence of the hotspot location on the microbial growth is investigated. To perform this a hotspot on a single pipe was modeled at three different locations.

Hotspot zone: heated pipe shaft through e.g. district heating

The pipes which are situated within the heated pipe shaft are marked red in Figure 4.5.1. The results of the comparison between the reference case and the pipe shaft heating case is shown in Figure 4.5.2.

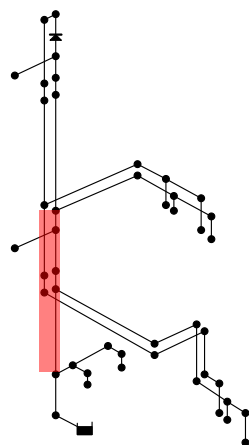


Figure 4.5.1 Reference case with pipe shaft heating. Heated zone is marked red.

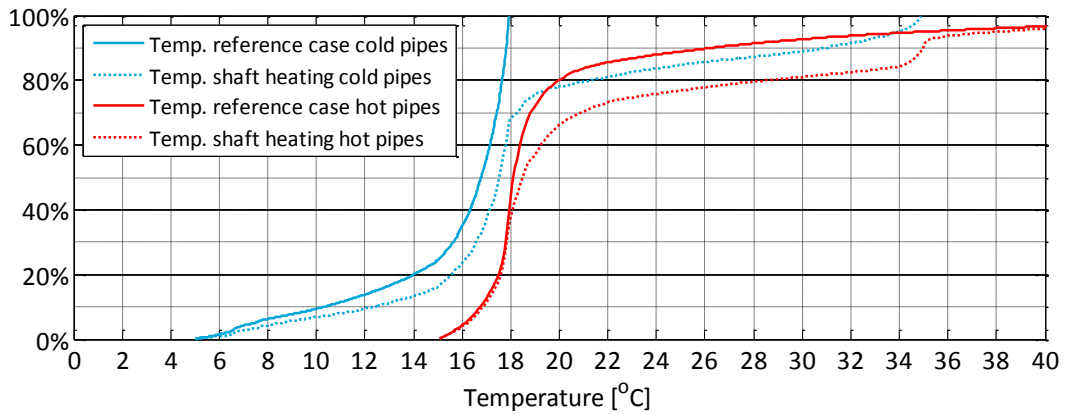
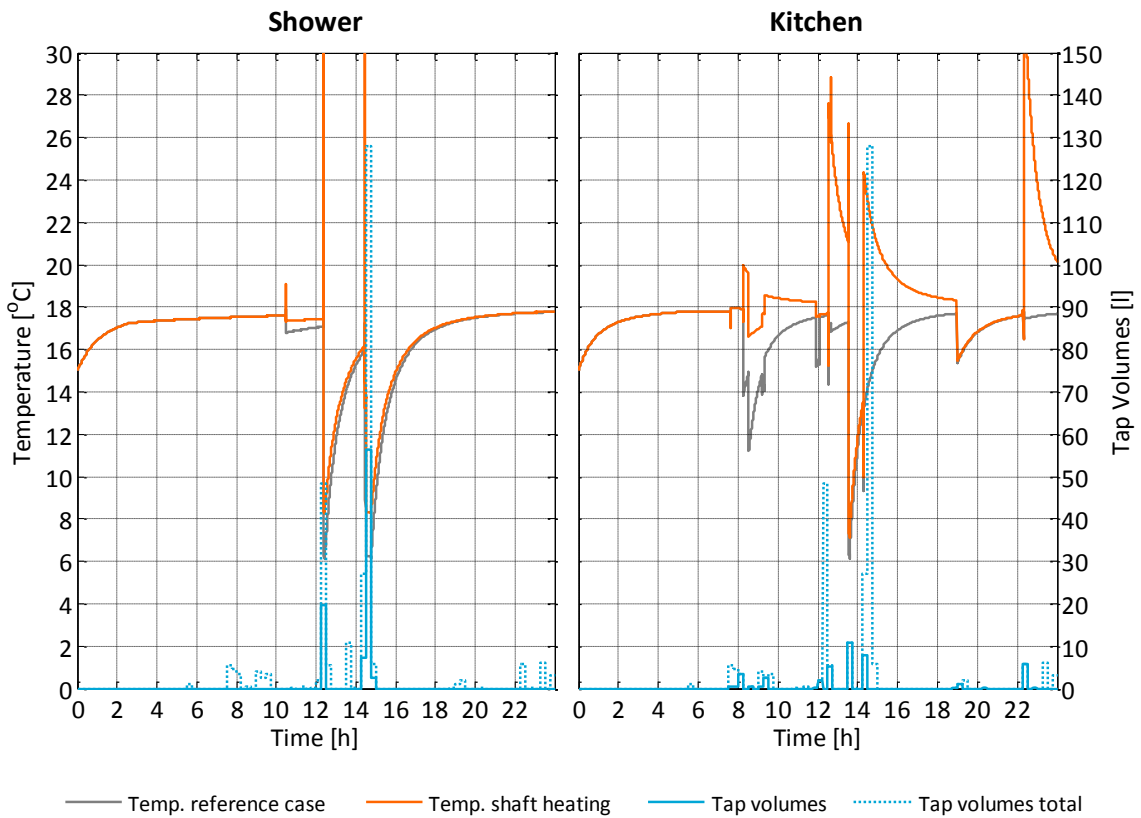


Figure 4.5.2 Comparison reference case and heated pipe shaft.

The continuous heating of pipes situated in the pipe shaft clearly affects the temperature of the cold pipes (Figure 4.5.2). Temperature peaks are visible when heated water reaches the shower tap. Cooling trajectories are visible at the kitchen tap when a small amount of water was tapped (<10 l).

Figure 4.5.3 (next page) shows the effect of the pipe shaft heating on the microbial growth at shower and kitchen tap.

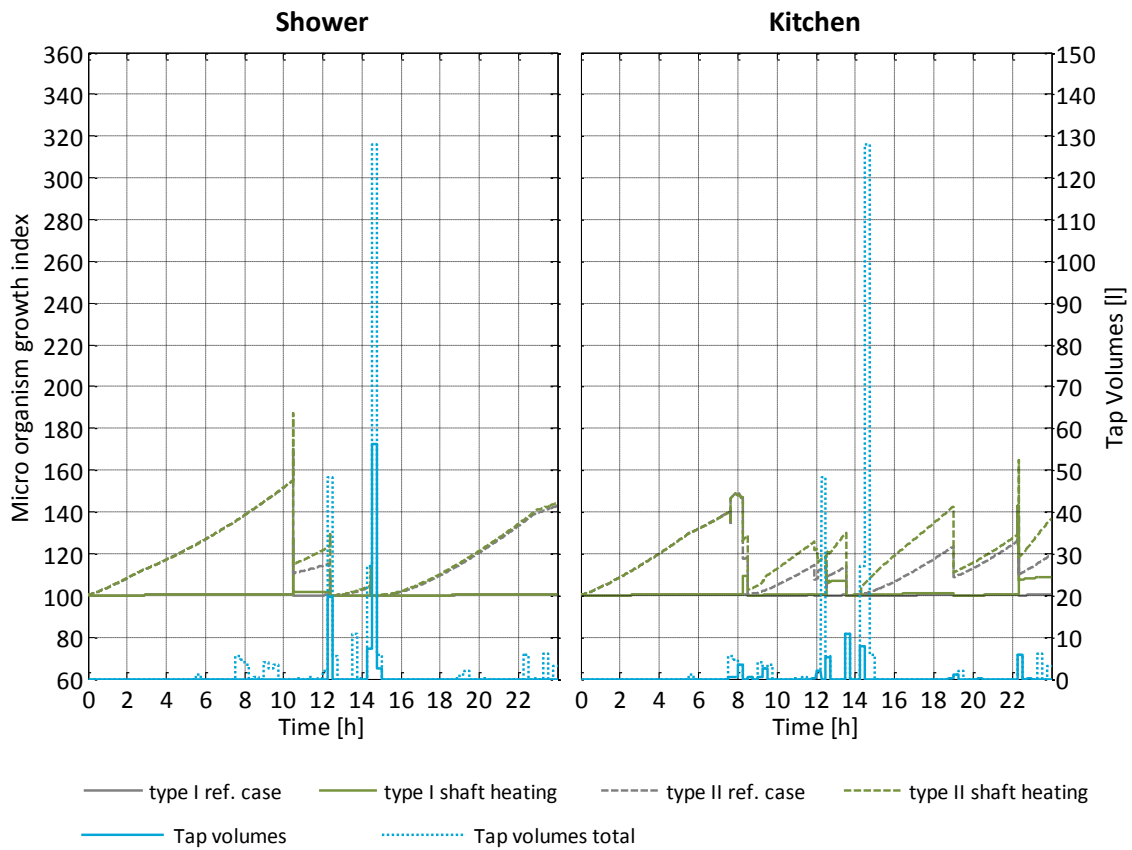


Figure 4.5.3 Microbial growth in heated pipe shaft case and reference case.

The effect of the heated pipe shaft on the microbial growth at shower and kitchen tap is minor for both micro organisms type I and type II (Figure 4.5.3). This is probably caused by the regular pipe flushing in the heated shaft since these pipes are part of the supply line to most tap points.

Effects of single hotspots locations on microbial growth

As mentioned above hotspots were modeled at three locations to investigate the effect of hotspot location on microbial growth. The hotspot locations are shown in Figure 4.5.4.

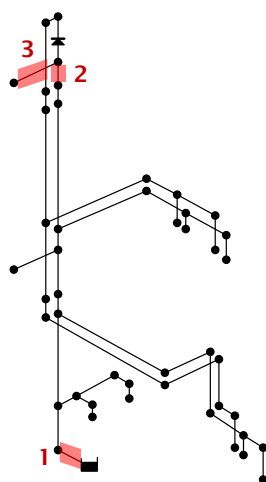


Figure 4.5.4 Reference case with single hotspot on different locations for several simulation:
 Run 1: location 1; much flushing since all trajectories to all demand locations pass this pipe.
 Run 2: location 2; moderate flushing, occurs on warm tap water demand (shower, washstand, kitchen tap)
 Run 3: location 3; no flushing during simulation time (24 h)

Since these single hotspots hardly affect the temperatures at the shower and kitchen tap and neither do significantly affect the whole network, the first three graphs (shower, kitchen, temperature frequency plot) are omitted and a frequency plot for microbial growth is shown only (Figure 4.5.5 below).

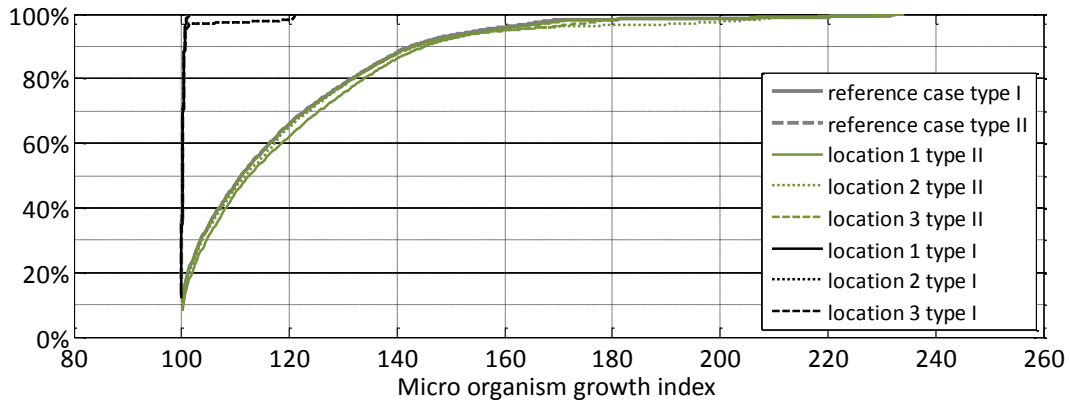


Figure 4.5.5 Effect of one hotspot at three different locations for Micro organisms type I and type II growth in all pipes at all time steps.

From the figure it is clear single hotspots hardly influence the growth of micro organisms with lower optimal growth temperatures (type II). This is different from the growth of micro organisms with higher optimal growth temperatures (type I). The latter show a large difference between locations which are flushed or not. It seems temperatures above 25°C are not of high influence on the microbial growth if the system is regularly flushed.

4.6 Relation temperature and demand volumes

To investigate the influence of the tap volume on the drinking water temperature two variations on the used demand pattern were calculated. The demands from the reference case were therefore multiplied by a factor 1/2 and a factor 2. The results are shown in Figure 4.6.1 (next page).

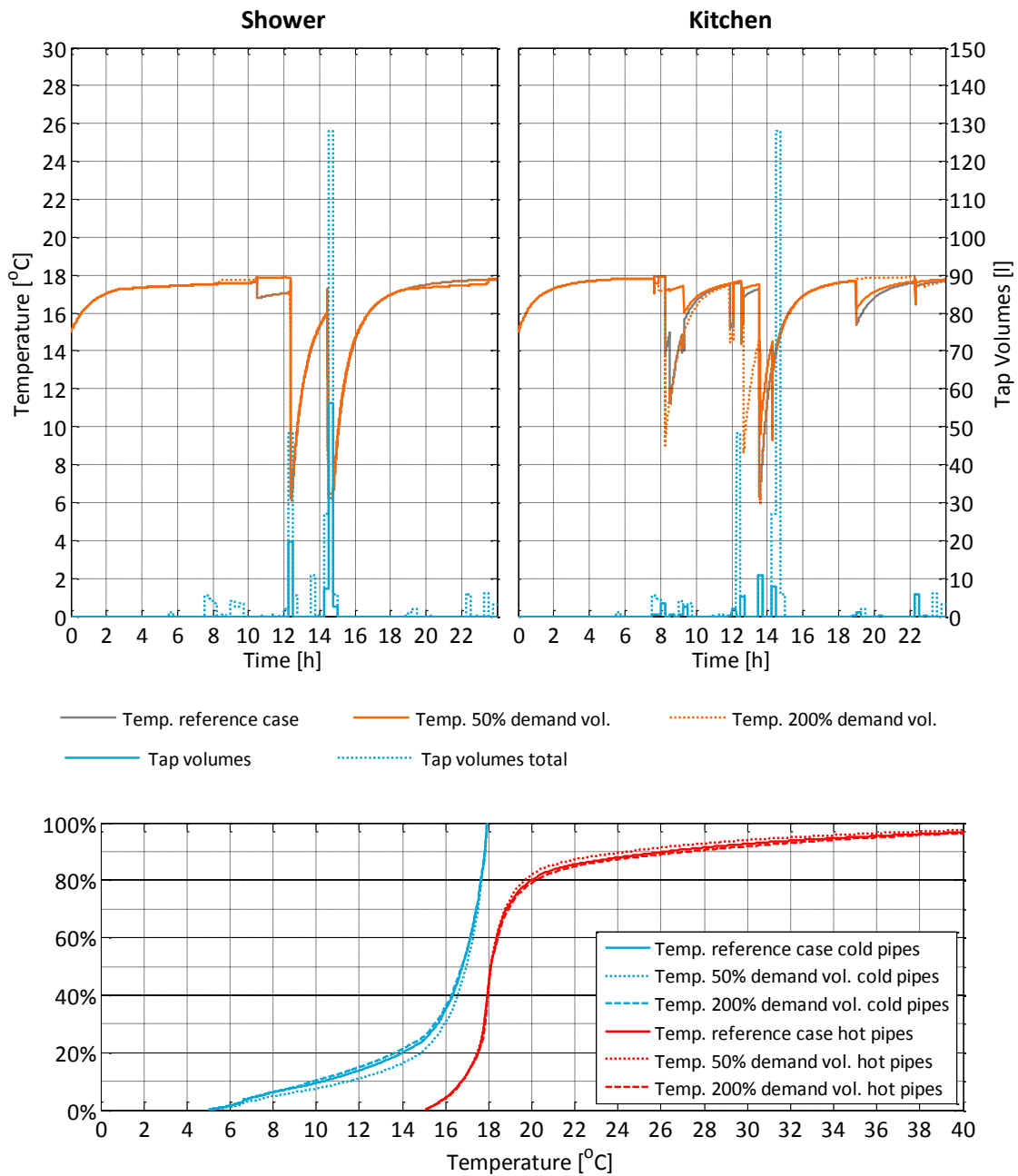


Figure 4.6.1 Results reference case compared to 50% and 200% demand volume cases.

The temperature in all pipes does hardly differ from the reference case (Figure 4.6.1b). Differences are visible for smaller demand volumes only (<10 l, see Figure 4.6.1a). It seems the demand volume does not influence the temperature in the network and at the tap if demand volumes are small.

4.7 Temperature during water demand

To clarify the extent to which water users are exposed to drinking water temperatures above the threshold of 25°C the water temperature during demand is shown in Figure 4.7.1. The drinking water temperature exceeds the threshold of 25°C in some cases only (summer, pipe shaft heating, single hotspot). These cases are shown next to the reference case. For the single hotspots the results of location 1 are shown only because the other two locations mentioned in Figure 4.5.4 are downstream of the shower and kitchen cold taps. Hence these

two hotspot locations have no influence on the temperature at the shower and kitchen cold taps.

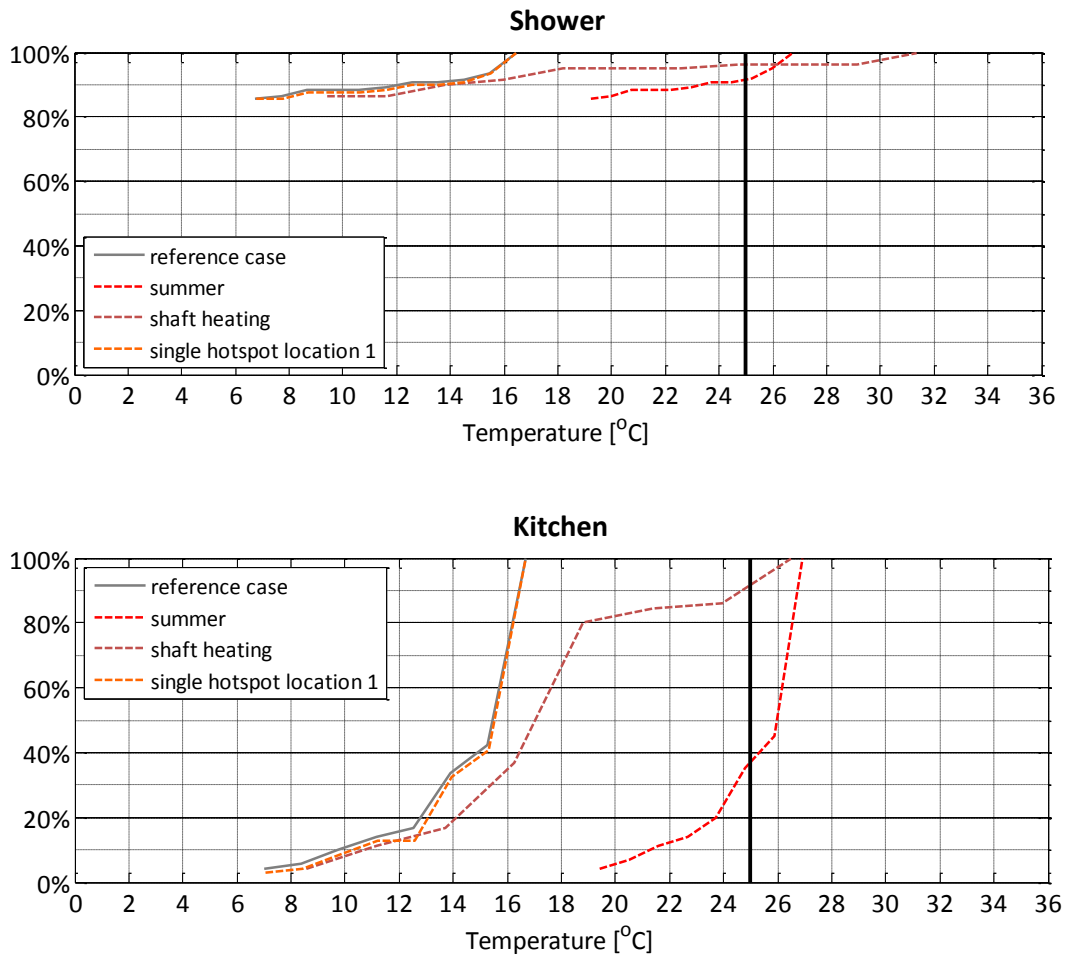


Figure 4.7.1 Drinking water temperatures during demand at shower and kitchen tap. The continuous line at 25°C is the temperature threshold.

The exposure to drinking water with at temperature above 25°C is higher at the kitchen tap. This is probably caused by the smaller demand volumes drawn from the kitchen tap compared to the shower tap. Hence less flushing occurs at the kitchen tap. This results in a broader frequency curve. Water which enters the cold shower tap is more intensive heated by pipe shaft heating than water which enters the cold kitchen tap. This effect can be explained by Figure 4.5.1; water which flows to the shower tap suffers more heating than water which flows to the kitchen tap.

5 Discussion

5.1 Temperature model

Since there is a high variability in domestic drinking water system layouts it is impossible to construct one model which will be valid for all specific situations. The focus of this research is therefore on the comparison of different scenarios, while assuming a certain network layout and boundary conditions (environment temperature, water temperature at supply point (Table 3.6.5)) and a certain demand pattern (Figure 3.5.1). Real domestic drinking water systems will consist of more variation in pipe environment. This emphasizes the limited validity range of this model; it forms a first exploration in the field of drinking water temperature modeling in domestic systems. The value of the model output has therefore to be characterized as relative and not as absolute. Although there is currently no comparison with real data the main conclusions will likely not be different if heating trajectories will undergo small changes after further validation.

Only one demand pattern was used to perform a convenient comparison between several scenarios and the reference case. This pattern shows demands during the whole day and could therefore be representative for a household of two retired persons. Demand patterns which show strong work-living pattern will likely result in more microbial growth during the day. However, the long period of stagnancy (Figure 3.5.1; 0.00 AM to 8.00 AM) creates the same effect at another point in time. For a better proof multiple demand patterns have to be created since SIMDEUM is a stochastic model. The next step in research is therefore the temperature calculation for a large number of demand patterns.

The diameters of the used network are slightly oversized compared to the current Dutch practical standards (ISSO 2003). This results in a larger system volume compared to domestic drinking water systems which are build conform the current practical standards. The results for microbial growth will therefore be conservative compared to the real situation. From all heat transfer processes which are described in paragraph 3.6 the effects outside the pipe are the bottle neck. The pipe environment is therefore of high influence on the drinking water temperature.

5.2 Models for microbial growth

Two simple models were used to simulate microbial growth for micro organisms of type I and type II. They were used to clarify that temperature exceedance do not necessarily lead to microbial problems. The reader has to bear in mind these simple growth models are very conservative since they assume unlimited external boundary conditions. Hence simulated micro organisms have unlimited nutrition and do not decay unless they pass the central heater. The effects of microbial growth can therefore overestimated during longer periods of stagnancy. To give the reader a broader view on microbial growth in the domestic drinking water system two microbial species were modeled. One with a higher optimal growth temperature (37°C; type I) and the other with a lower optimal growth temperature (25°C; type II). However, in reality a much broader spectrum of species will appear in the domestic drinking water system.

5.3 Results

As can be seen in all figures for drinking water temperatures at shower and kitchen tap the temperature at these tap points does never reach the boundary temperature of water at the supply point (5° for the reference case), even after large tap volumes. This can be explained by the effect the water is heated during transport between point of inflow (water meter) and

point of outflow (tap where demand occurs). Water which enters the network is heated very fast since the temperature gradient is maximal and flowing water is heated faster than water which is motionless. This results in a temperature increase of at least 1 degree during transport from water meter to tap.

This effect has consequences for the random daytime (RDT) measurements which are performed by water companies to check the drinking water temperature in their drinking water supply system. RDT sampling will therefore structurally show results which are higher than the real temperature in the drinking water distribution system. This effect will be maximal during winter when the temperature difference between water at the supply point and the domestic environment is maximal. This conclusion agrees with former research on drinking water temperature within the drinking water distribution system (Blokker and Pieterse-Quirijns 2013).

The graphs shown for shower, kitchen and bathroom washstand (Annex III) are based on the cold water data. Results for microbial concentrations can therefore be lower in reality if cold water is mixed at the tap with heated water. This is especially the case for the shower graphs and to a lesser extent for the kitchen and bathroom washstand graphs.

Summer scenario

To simulate a summer scenario an environmental temperature for summer was chosen. This temperature of 28°C is relative high but not unimaginable if temperatures above 30°C occur outside a house. During simulation the drinking water temperature in cold pipes exceeded the threshold of 25°C during 70% of the time (Figure 4.2.1 b).

From the results shown in Figure 4.2.2 and Figure 4.5.3 it seems hot summer days have more influence on microbial growth than hotspots. However, one has to bear in mind an ideal situation is modeled since no micro organisms during a pipe flush caused by a downstream demand. This does only hold in practice if there are no locations where micro organisms can accumulate (e.g. a tap which is unused for a long time). Next to this the influence of biofilms on the micro organisms in the bulk water phase is not implemented (see Annex I *Brief introduction on water quality within the domestic drinking water system* for a more comprehensive explanation about biofilms).

Different housing types scenario

To compare different housing types one type of apartment building was simulated and compared with the reference case and a network consisting of long horizontal pipes. The results (Figure 4.3.1) show the influence of other households on the drinking water temperature within the apartment which is at the end of the supply line. Houses which are linked to a collective drinking water supply system (apartments) seem to benefit from each other's influence on the flushing of the collective system. There is a slight difference between the results of the apartment network and the network which consists of longer horizontal pipes. In the apartment case all pipes (Figure 3.5.3) were exposed to the same environmental temperature of 18°C. In reality lower temperature could be expected for the public domain within the apartment building. The drinking water temperature in the apartment case will therefore be lower if this effect would be incorporated in the model.

Pipe concealment scenario

The heat capacity of the small air layer around concealed pipes is approximately a factor 10^4 smaller than the heat capacity of the water. The influence of this air layer on the drinking water temperature was therefore neglected. The air layer was modeled like a static thermal resistance (insulation) where heat is transferred through conduction only. This means the heat transfer around concealed pipes is not temperature dependent like normal pipes which are affected by natural convection. Hence concealed pipes are heated more slowly compared

to pipes which are exposed to natural convection (Figure 4.4.2). Although this effect is not verified by measurements, the results correspond to daily practice.

Hotspot scenarios

The results from the hotspot scenarios are remarkable. As can be seen from Figure 4.5.2 pipe shaft heating does highly influence the temperature at the tap and in the whole network. However high concentrations of microbial growth are not found in the domestic drinking water system (Figure 4.5.3). Especially the growth of micro organism type II does hardly differ from the reference case. However, one has to bear in mind the considerations mentioned in the discussion about the summer scenario.

Single hotspots seem to have hardly influence on the microbial growth in the system unless they are situated at places which are not regularly flushed (Figure 4.5.5). The single hotspot at location 3 (washing machine supply line) shows the largest microbial growth for micro organisms of type I.

Tap volume change scenario

To further investigate the influence of the demand volume on the temperature and microbial growth in the domestic drinking water system the reference case was compared to two other cases where tap volumes were multiplied and divided by a factor two. The effects of changing demand volumes are surprisingly small (Figure 4.6.1). This emphasizes the conclusion moment of demand has much more influence on the temperature in the domestic drinking water system than the volume which is drawn at that moment.

In paragraph 3.4 the effect of a possible increase in demand volume was mentioned when the user flushes water away which is unwanted because of its temperature. This may take place when the user wants cold water for consumption. The assumption was made that this effect does not influence the temperature in the system. The results of the tap volume change scenario (Figure 4.6.1) show that this assumption can be made since tap volume changes hardly influence the drinking water temperature in the domestic drinking water system and at the tap.

Temperature during water demand

For a comparison between the three scenarios which create temperatures above 25°C (summer, pipe shaft heating, single hotspot) Figure 4.7.1 was shown. It shows the drinking water temperatures *during demand*. The influence of tap volumes on the temperature during demand is highly visible through the differences between the results for shower and kitchen tap. These figures also underline the vast influence of the environment temperature. This is clearly visible in the result for the bathroom washstand and toilet washbasin (Annex III) where the temperatures during demand in summer scenario are always above the threshold of 25°C.

5.4 Model applications

During this research the DDWT model was used to calculate different scenario's on temperature and microbial growth only. However, the model can also be used contrariwise: the checking of cooling trajectories of hot water pipes since the temperature of these pipes have to be below the threshold within a certain time period.

The determination of hot water waiting times is another application in which the DDWT model can play a role.

6 Conclusions and recommendations

During this research the main focus was on modeling the drinking water temperature in domestic drinking water systems to answer the second research question: *How can the drinking water temperature in DDWS be modeled?* The first research question (*How is the temperature related to water quality in DDWS?*) was elaborated less detailed than the second is. However the results of the literature study (Annex I) and the results of this research (chapter 4) are sufficient to answer the first research question and to create a conceptual framework for the second research question.

The conclusions which can be drawn from the results and discussion section are listed below:

- The drinking water temperature within domestic drinking water systems can be modeled using SIMDEUM, EPANET and EPANET MSX.
- Demand patterns in the domestic drinking water systems are the key factor in drinking water temperature and microbial growth.
- Since drinking water is heated while it is transported from supply point (service pipe) to demand point (tap) RDT sampling performed by the Dutch water companies will structurally show results which are at least 1-2°C above the actual water temperature within the drinking water distribution system.

Following to these conclusions the following considerations are recommended:

- Validation of the drinking water temperature model to check the results from this research. Validation can be performed by the use of temperature and demand measurements at all tap points in the domestic drinking water system. Since all drinking water demands in the domestic drinking water system influence the drinking water temperature it makes less sense to measure the temperature at only one or two tap points. There are currently sensors available which can be installed outside pipes and measure both water temperature and flow (Kleijntjens 2013). These sensors could possibly be used to perform such measurements.
- During this research one demand pattern was used. It is recommended to further investigate the influence of different demand patterns on the drinking water temperature and microbial growth.
- It is recommended to further investigate the heating of water while it is transported through the domestic drinking water system to correct the RDT sampling method for this effect.

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List of variables

Variable	unit (SI)	description
D	m	pipe diameter
d	m	pipe wall thickness
δ_{air}	m	thickness air layer around concealed pipes
ρ	kg/m ³	density
m	kg	mass
c_p	J/(kg·K)	heat capacity of the water
μ	Pa·s	dynamic viscosity
μ_{δ}	Pa·s	dynamic viscosity of fluid at the pipe wall
ν	m ² /s	kinematic viscosity
v	m/s	velocity averaged over pipe diameter
v_s	m/s	velocity on surface of pipe wall
ΔT	K	temperature difference
τ	s	residence time
λ_p	W/(m·K)	thermal conductivity of the pipe wall
λ_w	W/(m·K)	thermal conductivity of the water
h	W/(m ² ·K)	heat transfer coefficient
h_{comb}	W/(m ² ·K)	combined heat transfer coefficient

Annex I

Brief introduction on water quality within the domestic drinking water system

Chemical composition of water in DDWS

The exact chemical composition in drinking water depends much on the raw water source (ground water, surface water) and the treatment steps of the involved DWTP. The thresholds of chemical compounds in drinking water are specified in the Drinkwaterbesluit. Points of attention within DDWS are the increase of ion concentrations due to stagnant water in pipes, taps, etc. Research has demonstrated lead, copper, nickel and chrome concentrations above the threshold mentioned in the Drinkwaterbesluit (Slaats, Blokker et al. 2008). The saturation of the water plays a great role in the leaching of metals. The pH of the water should therefore not be very low compared to the equilibrium pH. Otherwise the solvency of the water will cause a high leaching rate (de Moel, Verberk et al. 2006). The temperature by itself does also influence the leaching of metals from the pipe wall or fittings. Temperature gradients have influence on the release of copper ions (Rushing and Edwards 2004). Hence hotspots can cause copper leaching when cold water flows through a pipe which is heated by an external heat source. The release of lead from brass fittings can increase when exposed to higher temperatures (Sarver and Edwards 2011).

Microbial properties of water in DDWS

Equal to the chemical composition, the microbial composition of the water depends mostly on the raw water quality and the effectiveness and/or the efficiency of the water treatment. Micro organisms which occur in water are viruses, bacteria, protozoa and fungi. These micro organisms can be classified as pathogens, non-pathogens or as opportunistic pathogens. Pathogenic micro organisms should not be present in drinking water. Indicator bacteria are used to check the safety of the drinking water. The *Escherichia coli* or E. coli is the most well-known indicator bacteria. Since clean and safe drinking water is assumed in this research, pathogenic micro organisms are not accounted in this research. Non-pathogenic micro organisms are always present in drinking water. These micro organisms are responsible for the regrowth in DWDS and DDWS. They are also called commensal bacteria which mean they use other organisms without impairing them. The opportunistic pathogens derive special attention. These bacteria species are normally non-pathogenic; however, the combination of higher numbers and immunocompromised people can be dangerous. The four types of micro organisms do also use each other to survive and reproduce. The viruses are an example of both processes; they use bacteria to survive and to spread themselves when these bacteria die. Bacteria in their turn, use sometimes protozoa to protect themselves.

Biofilms

Microbial activity occurs in two distinct forms: freely dispersed in the aqueous phase and attached to a wall within microbial communities. The latter is called biofilm and can theoretically occur at all surfaces in contact with water (Walker, Surman et al. 2000). From estimations based on empirical data it is estimated that only 5% of all microbial cells present in water occur in the water phase. The bulk of 95% exists in biofilms attached to the walls

(Moritz, Flemming et al. 2010). These biofilms are of interest because of their ability to protect inliving bacteria and other micro organisms against changing hydraulic regimes and disinfection measures. This means that biofilms can have effects on the aesthetics (color, odor, taste) and the public's health (Oosterholt, Veenendaal et al. 2007, Moritz, Flemming et al. 2010). Biofilm is related to many (potential) problems in drinking water distribution: complaints because of bad color, odor or taste, false positive bacteriological tests (Oosterholt, Veenendaal et al. 2007), high plate counts, abundant growth of (opportunistic) pathogens (Percival, Walker et al. 2000, van der Wielen and van der Kooij 2009, Douterelo, Sharpe et al. 2013), discoloration of drinking water and an increase of wall friction. Perhaps the largest potential problem of biofilms is the relation to the regrowth of coliforms in drinking water (Walker, Surman et al. 2000). Despite the lack of evidence that conclusively supports this hypothesis, a large number of researchers have found evidence of coliform regrowth (Percival, Walker et al. 2000).

Prioritized opportunistic pathogens

As a result from research performed by KWR, four species of micro organisms were selected which are prior in future research (van der Wielen and van der Kooij 2009). These micro organisms are prioritized because of their potential danger, the fact they are spread through the DWDS and their potential growth when drinking water temperatures increase. They are listed in Table 5.4.1.

Name	Multiplication in drinking water	Growth T<20°C	Growth around T=25°C	Growth 25<T<30°C
<i>Legionella pneumophila</i>	Only by a protozoa host	Almost no growth	Only <i>Legionella anisa</i>	<i>anisa</i> and possibly <i>pneumophila</i> spp.
Non-tuberculosis mycobacteria (NTM's)	With or without a protozoa host	No growth	Well able to grow	Well able to grow
<i>Pseudomonas aeruginosa</i>	With or without a protozoa host	No growth	Able to grow	Able to grow
Pathogenic fungi	In sediments	No growth below 10°C	Well able to grow	Well able to grow

Table 5.4.1 Micro organisms with high priority and their temperature related characteristics.

Researchers from KWR presume, based on former research, growth of *Legionella pneumophila* only at higher temperatures (T>30°C) because of the – possibly competitive – growth of *Legionella anisa* at temperatures between 25 and 30°C (Oosterholt 2013). From the ca. 250 cases of *Legionella* infection which occur yearly in the Netherlands, no one was credited to the *anisa* variant (van der Kooij, Wubbels et al. 2007). The attention to the growth of *Legionella pneumophila* is therefore not very urgent at temperatures below 30°C. However, there are also studies (Moritz, Flemming et al. 2010) which emphasize the potential growth of *Legionella pneumophila* at temperatures around 25°C. *Pseudomonas aeruginosa* deserves special attention because increase of this bacterium was shown especially in DDWS (van der Wielen and van der Kooij 2009, Moritz, Flemming et al. 2010).

Stimuli of microbial activity

Although there are a lot of parameters which influence the growth of micro organisms, there are five main parameters which are cause of this undesirable effect. These parameters are listed below.

- Presence of nutrients also mentioned as AOC (Percival, Walker et al. 2000, Ainsworth 2004). This means organic bindings which can be assimilated by heterotrophic organisms. The higher the concentration of AOC, the higher the activity of the heterotrophic organisms will be. Organisms are called heterotrophic when they use organic material for their own growth (heterotrophic metabolism).
- Temperature. The temperature of the drinking water plays a large role in microbial activity. The temperature functions therefore often as surrogate parameter to indicate microbial growth. Temperatures between 25 and 37°C are optimal for the growth of most micro organisms with pathogenic characteristics (van der Wielen and van der Kooij 2009). Microbial activity is hardly present at temperatures below 15°C (Percival, Walker et al. 2000, Ainsworth 2004, Gray 2008).
- Pipe material. The type of material being used in DDWS plays a large role in biofilm development. Materials which stimulate bacterial growth include rubber, silicon, PVC, PE and bituminous coatings (Percival, Walker et al. 2000). Copper is related to less biofilm growth compared to plastics (Rogers, Dowsett et al. 1994, Lehtola, Miettinen et al. 2004, Oesterholt, Veenendaal et al. 2007, Moritz, Flemming et al. 2010).
- Hydraulic regimes (Walker, Surman et al. 2000, Ainsworth 2004). The pattern of water flowing through a DDWS is important for regrowth since micro organisms benefit from slow-flow situations (Lautenschlager, Boon et al. 2010). Next to this highly varied flows result in higher species richness (Douterelo, Sharpe et al. 2013).
- Presence of sediment. Several references (Walker, Surman et al. 2000, Bartram, Cotruvo et al. 2003) mention the relation between microbial growth and the presence of sediments. Sediments are especially linked to the build-up of biofilms.

Briefly said the microbial activity can be bounded by limitation of nutrients and sediments in the DWTP, maintaining the temperature and preclusion of stagnant water through oversized systems and dead ends.

Other biological activity

Water may also contain invertebrates which are not belonging to the group of micro organisms. However these organisms do not create a potential risk by themselves. They can be used as harbor by opportunistic pathogens like *Pseudomonas* spp. (Percival, Walker et al. 2000).

Annex II

Legislation and standards in drinking water distribution

Legislation and standards

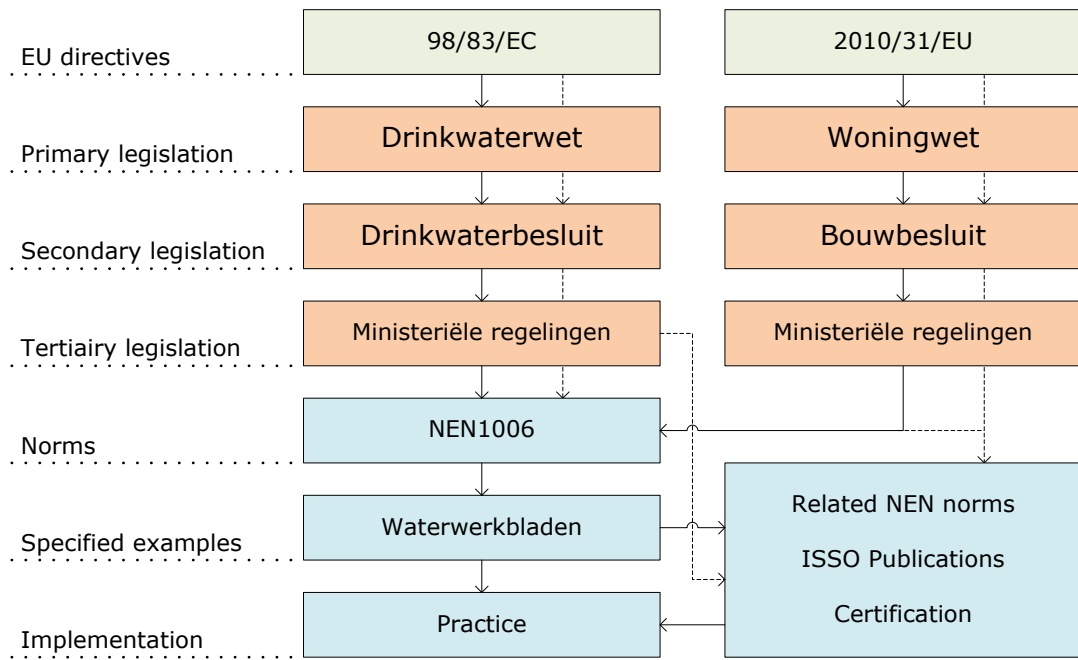
The current situation, described in chapter three, would not have been there without the legislation, directives, regulations, norms, publications and certification which are currently present. In the paragraphs below the different types of legislation (and their relation) is briefly described. Next to this the temperature threshold in the Netherlands is discussed.

EU legislation and standards

The EU legislation on drinking water is formed by the 98/83/EC directive. According to the constitutional relations between the EU and the member states, the latter have to implement the EU directives in their national legislation. Although the directive 98/83/EC has standards for the chemical and microbial condition of the drinking water, a temperature threshold is not given. National standards of member states shall not be less stringent than the parameter values mentioned in annex I (part A and B) of the directive 98/83/EC.

Dutch legislation and standards

The drinking water quality in the Netherlands is juridical maintained by the Drinkwaterwet (Drinking water Directive). This directive commenced at 1 July 2011 as the implementation of directive 98/83/EC into the former Waterleidingwet (directive on water distribution) and forms the framework for other (secondary) forms of legislation. This secondary legislation is formed by the Drinkwaterbesluit (Drinking water Decree). In this juridical statement the parameter values which have to be met are included. An example of tertiary legislation under the Drinkwaterwet is the regulation on *legionella* prevention (Ministeriële Regeling Legionellapreventie) which is a result of the temporal *legionella* prevention regulation which came into force after the *legionella* problems in Bovenkarspel (1999).



Framework of drinking water and DDWS standards in the Netherlands. Green blocks are supra national legislation (EU directives), orange blocks are national legislation and blue blocks are all kinds of norms, certification and examples to elaborate, concretize and guarantee the legislation. Dotted lines are connections between different “layers” of legislation or standards.

Beneath the Drinkwaterbesluit, the norms can be found which translate the parameter values from the drinking water act in practical norms.

Standards in other EU countries

Within the framework of this research the standards of different countries were investigated on the presence of a temperature threshold. The literature research on internet included 17 countries: Austria, Belgium, Czech, Denmark, France, Germany, Great Britain, Greece, Ireland, Italy, Luxembourg, Portugal, The Netherlands, Norway, Spain, Sweden and Switzerland.



Visualization of result literature research on temperature thresholds in drinking water legislation. Red means the absence of a strict temperature threshold, green the presence and red-green striped countries give only advice temperature thresholds in their legislation. Transparent countries are not currently member state of the EU.

It was found that in the Netherlands only there is a strict threshold for the temperature of drinking water at the tap. Sweden does have a temperature threshold, but measured directly after treatment and not at the tap. Some other countries mention an advice temperature (Denmark) or use the temperature as an indicator parameter (Austria, Belgium, France). This means the temperature function only as an indicator for possible disturbances in the water quality and not as strict threshold.

NEN1006

The norm NEN1006 (also called AVWI-2002) gives the requirements with respect to public health, safety and expediency of water supply installations. The NEN1006 is mentioned in both the Drinkwaterbesluit and the Bouwbesluit (construction decree) from which the latter forms the secondary legislation under the Woningwet (directive on residential). The NEN1006 was most recently modified in 2002 and supplemented between 2002 and 2012 by three "modification notes" (A1-A3). Hence the norm which is currently valid is officially called the NEN1006:2002/A3. For the sake of readability it will be mentioned as "NEN1006". The NEN1006 gives the basis which a DDWS should meet:

"A DDWS shall be designed such that:

- a. the flow and pressure at concerned tap points and connection points for appliances is available;*
- b. the water at the tap is reliable with respect to the public health;*
- c. it is safe for the lives and/or properties of the user or third parties;*
- d. the supply of drinking water to third parties is not negatively influenced;*
- e. noise nuisance is avoided;*
- f. it not to the spill of water and/or energy*
- g. a long-term and undisturbed use could be expected*
- h. the quality of different types of water not is influenced by cross connections or otherwise is negatively influenced." (translated citation from NEN1006)*

The basis for a proper design is therefore given. This basis is further elaborated in several regulations described in the NEN1006 which are listed below.

- *Chapter 2: General technical conditions:* pressure and temperature of water within domestic water supply installations, pipe materials and appliances, mandatory pressure tests, commissioning and earthing.
- *Chapter 3: Conditions for the design:* grouping, pipes in buildings, closure and tap properties, pipes in the ground outside buildings, fixation of pipes, different water supply systems in one allotment, connection and safeguard of appliances.
- *Chapter 4: Conditions for special facilities:* drinking water reservoirs, breakers and reservoir cisterns not used for drinking water, pressure increase installations, heat tap water appliances, firefighting appliances, local water treatment, domestic water installations.

In paragraph 2.1.2 of the NEN1006 temperature norms are given for cold and heat water pipes. According to the NEN1006 the temperature should not be higher than 25°C. Next to this, heat water in pipes should cool down to a temperature equal or below to 25°C when there is no heat water demand. The NEN1006 is deliberately maintained abstract to keep the application very broad because of the variations in water quality and the circumstances of water treatment.

Implementation of NEN1006 in practice

To fill the – deliberately created – gap between the NEN1006 and practice several publications are guiding for implementing the NEN1006 in practice.

Waterwerkbladen

The Waterwerkbladen, which were until recently called “VEWIN Werkbladen” are a more detailed elaboration of the NEN1006. In the Waterwerkbladen a broad variation of instructions for all kinds of water applications can be found. Each Waterwerkblad is a detailed description of one subject from the NEN1006. The statements from the Waterwerkbladen must be seen as boundary conditions wherein the DDWS has to be to meet the standards of the NEN1006. Each Waterwerkblad start therefore by elaborating the regulations from the NEN1006 which are relevant for the subject of that specific Waterwerkblad. Waterwerkbladen are available from www.infodwi.nl.

ISSO Publications

ISSO is the organization which was found in 1974 by three organizations in the field of heating and air treatment. Several advisor and branch organizations like Uneto-VNI participate in ISSO. ISSO provides knowledge to installers, fitters and electro technicians. Disappointing results of *legionella* prevention and backflow safeguarding published in a report of the former Ministry of Housing, Spatial Planning and Environment (VROM) (Versteegh, Brandsema et al. 2007) led to the Action Plan Safe Water Supply Installations (Actieplan Veilige Leidingwaterinstallaties) from Uneto-VNI and ISSO (Scheffer 2013). Since 2007 several publications were published which are listed³ in the table below:

Number	Name	Description
ISSO 30	Leidingwaterinstallaties in woningen	Manual for design and realization of DDWS which meet the standards
ISSO 30.3	Waterslag in tapwaterinstallaties	Solutions for water hammer problems in DDWS
ISSO 30.4	Warmteterugwinning uit douchewater	Application of heat recovery systems in showers

³ The publications related to DDWS are listed only.

ISSO 30.5	LegionellaCode	Manual for design and realization of legionella safe DDWS
ISSO-SBR 811	Integraal ontwerpen van legionellaveilige woningen	Brochure on the avoidance of hot spots in the design of DDWS
N.A.	ISSO-Kleintje Legionellapreventie	Small brochure about legionella prevention
N.A.	Checklist 'Hotspots' in waterleidingen	Checklist for hotspots in DDWS
BRL 6000-07	Leidingwaterinstallaties van individuele woningen	Certification for DDWS from KOMO INSTAL certified installer/fitter

Current developments: NEN-EN-806

In July 2011 the Drinking water Directive and the subsequent Drinking water Decree came into force and replaced the former Waterleidingwet and Waterleidingbesluit. This change has to be incorporated in the NEN1006. The NEN1006 is currently a national norm. This will change in 2013 by the introduction of the NEN-EN-806. This is the EU broad norm which consists of five parts (Meerkerk 2013 [1]). The NEN1006 will remain, but as a “translation” of the NEN-EN-806. This means a part of the aspects from the NEN-EN-806 will be used for the NEN1006 (Scheffer 2013). The NEN-EN-806 consists of the following parts:

- NEN-EN-806-1: General
- NEN-EN-806-2: Design
- NEN-EN-806-3: Pipe dimensions
- NEN-EN-806-4: Realization
- NEN-EN-806-5: Operation and maintenance

The Waterwerkbladen will also be adapted to the NEN-EN-806.

Temperature norm discussion

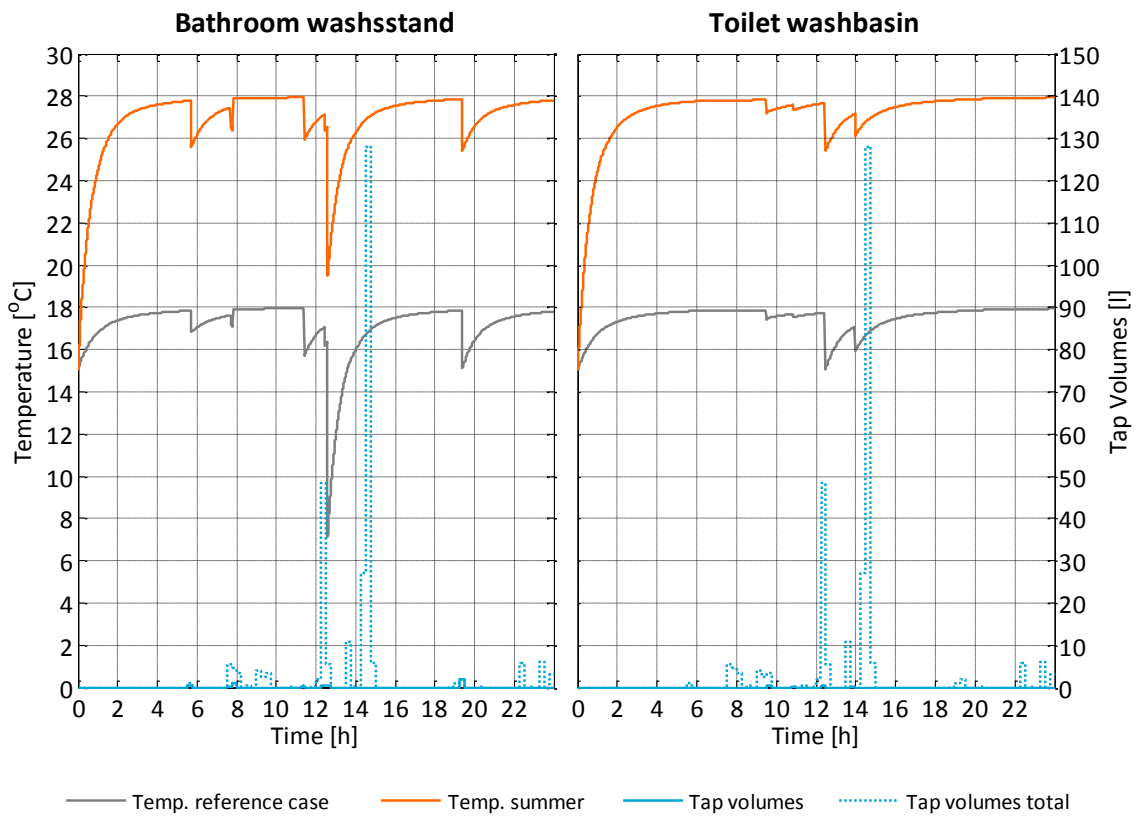
The choice for a threshold of 25°C was based on the combination of practicability, risk acceptance - the 25°C threshold is often related to the minimum temperature for *Legionella Pneumophila* growth - and the fact the 25°C temperature threshold was already present in the precursor of the Drinking water Decree; the Waterleidingbesluit (Scheffer 2013). This choice implies the possibility of maintaining the temperature equal or below 25°C, which is hardly argued or proved. In practice there are no measurement protocols for installers/fitters to determine exactly if the temperature meets the standards (Scheffer 2013). There are only checklists available like the ISSO checklist for hotspots in DDWS. Next to this the urgency of a temperature below 25°C because of the growth of *Legionella Pneumophila* is also under discussion.

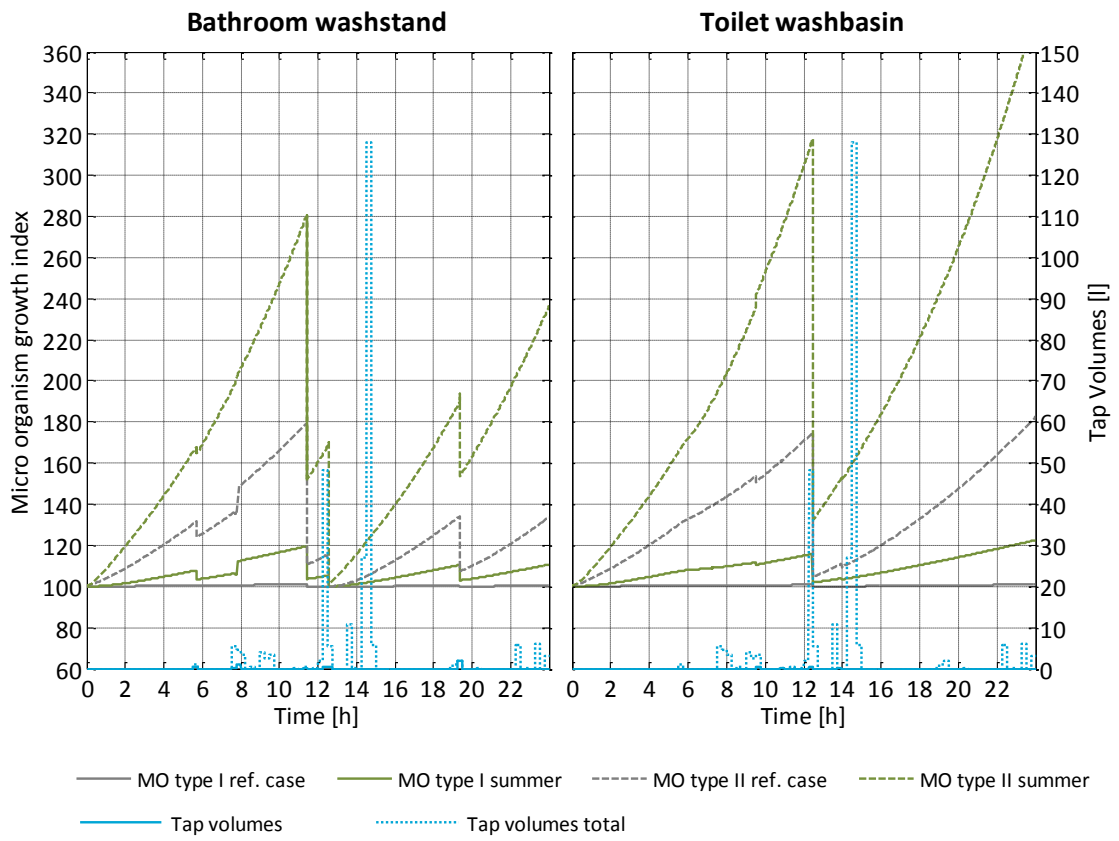
Annex III

Figures for bathroom washstand and toilet washbasin

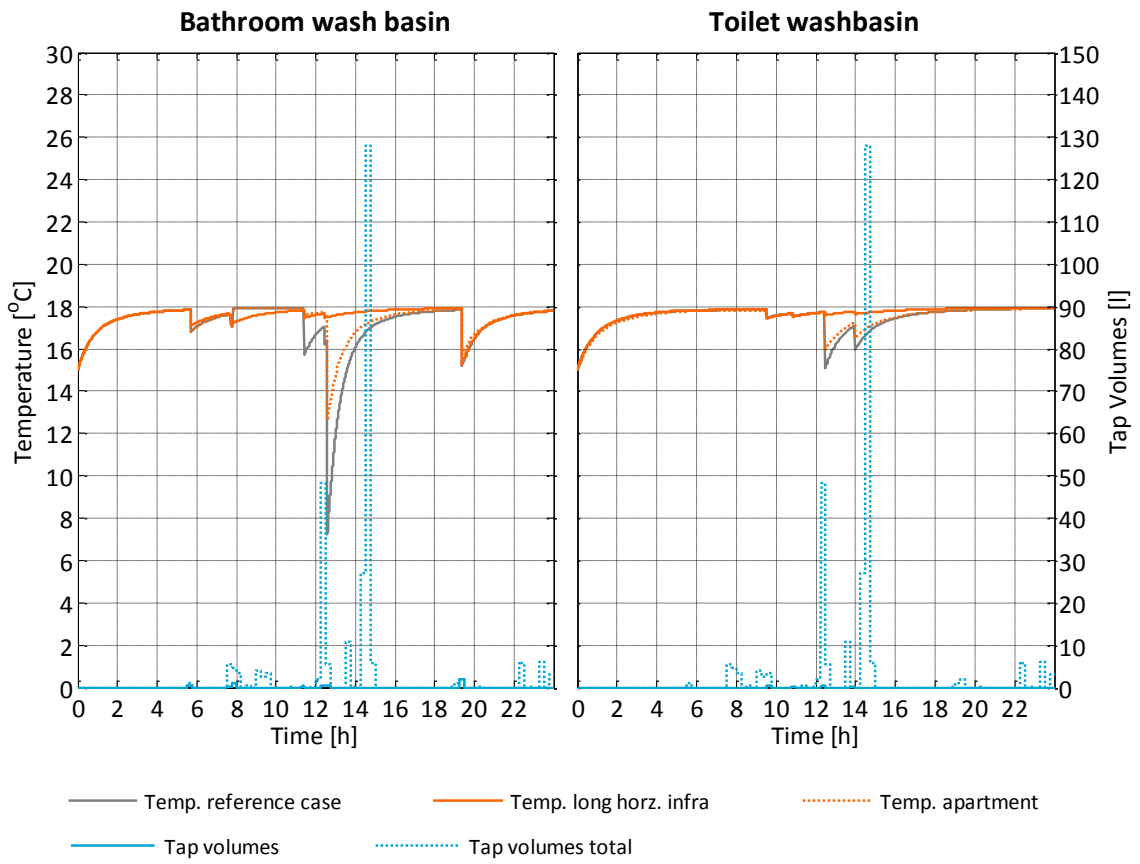
In this annex the results on local scale for the bathroom washstand and toilet washbasin are shown to complete the perspective on demand points which are of interest because of possible health risks.

Reference case vs. hot summer day

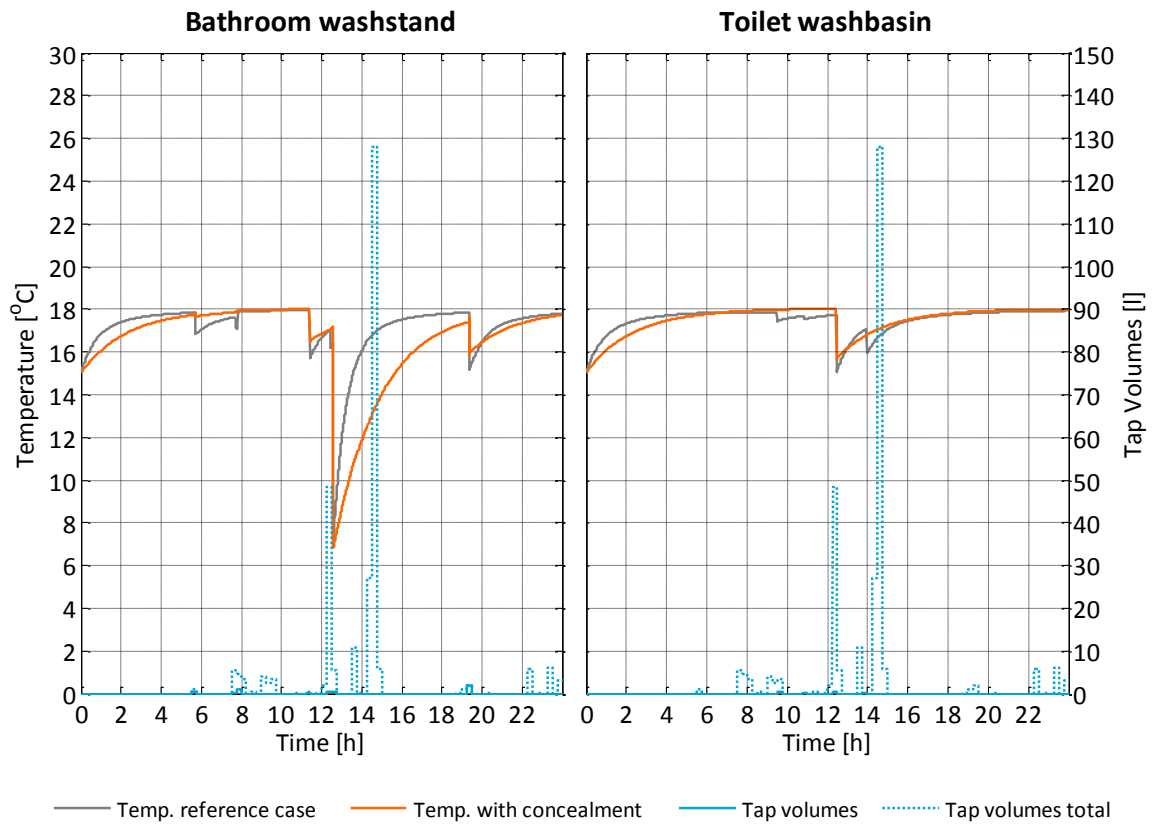




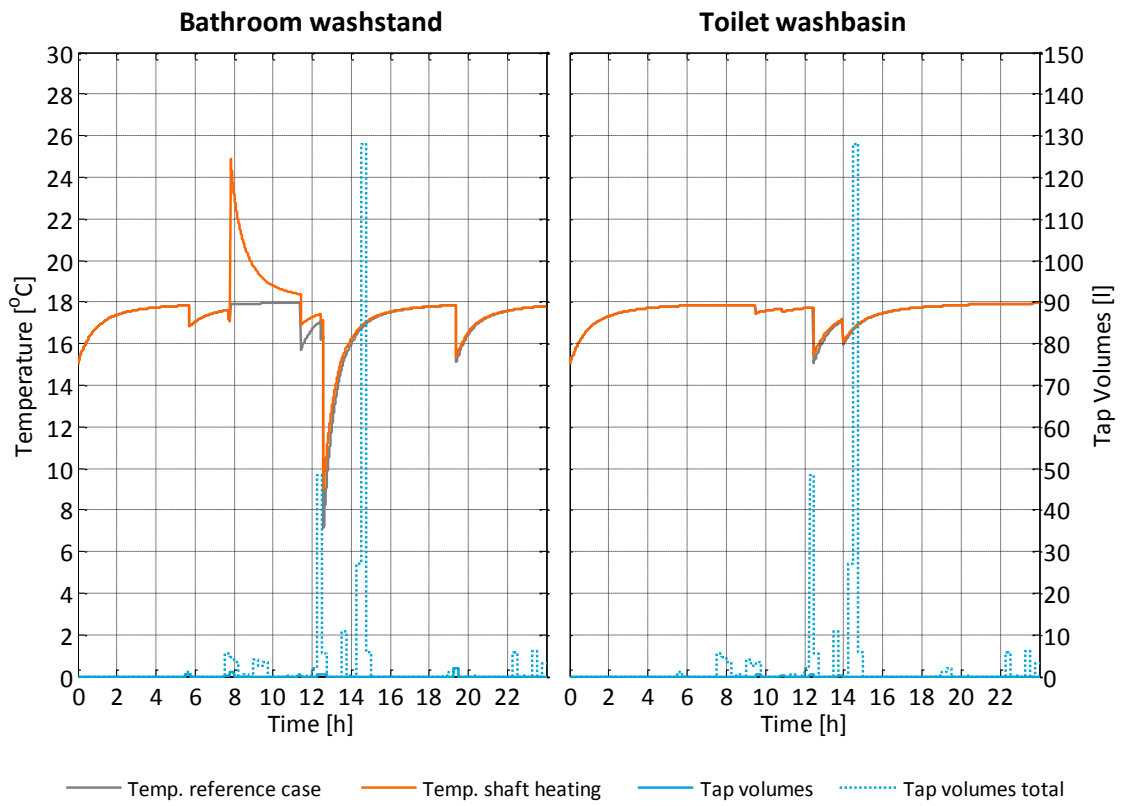
Different housing types comparison

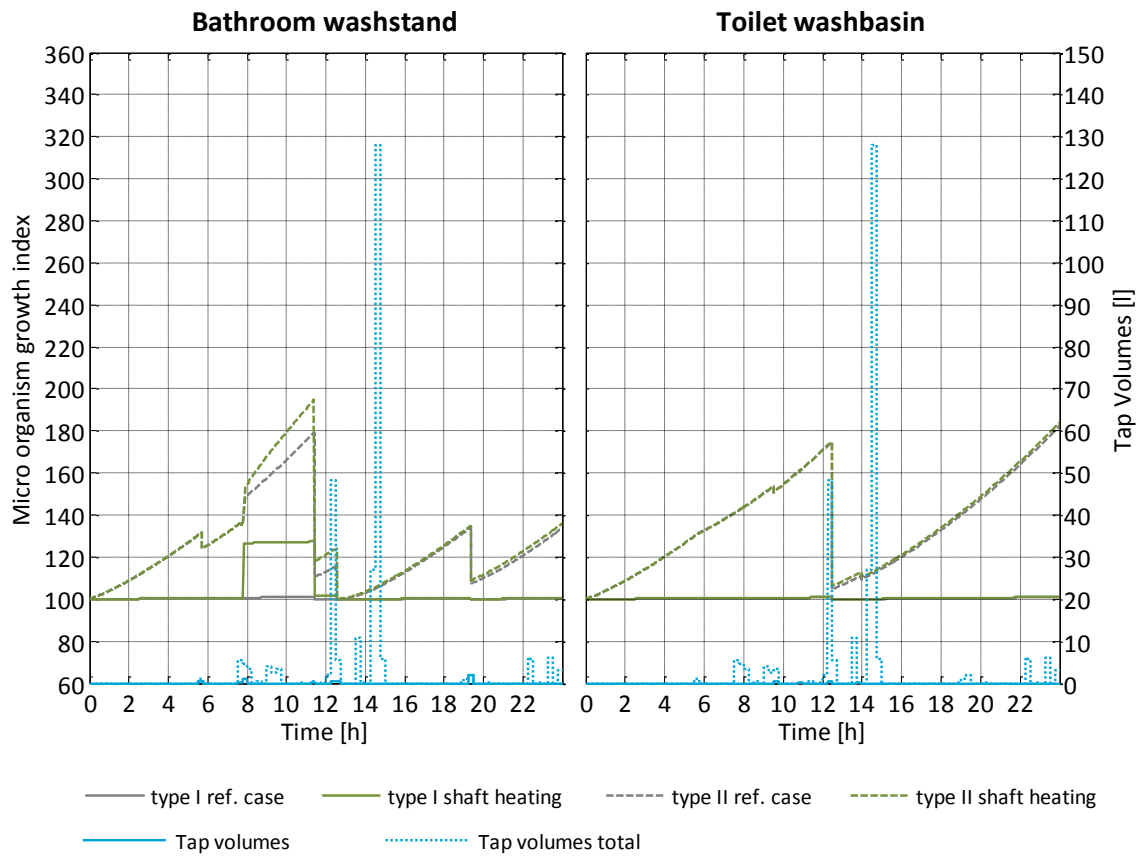


Reference case vs. pipe concealment

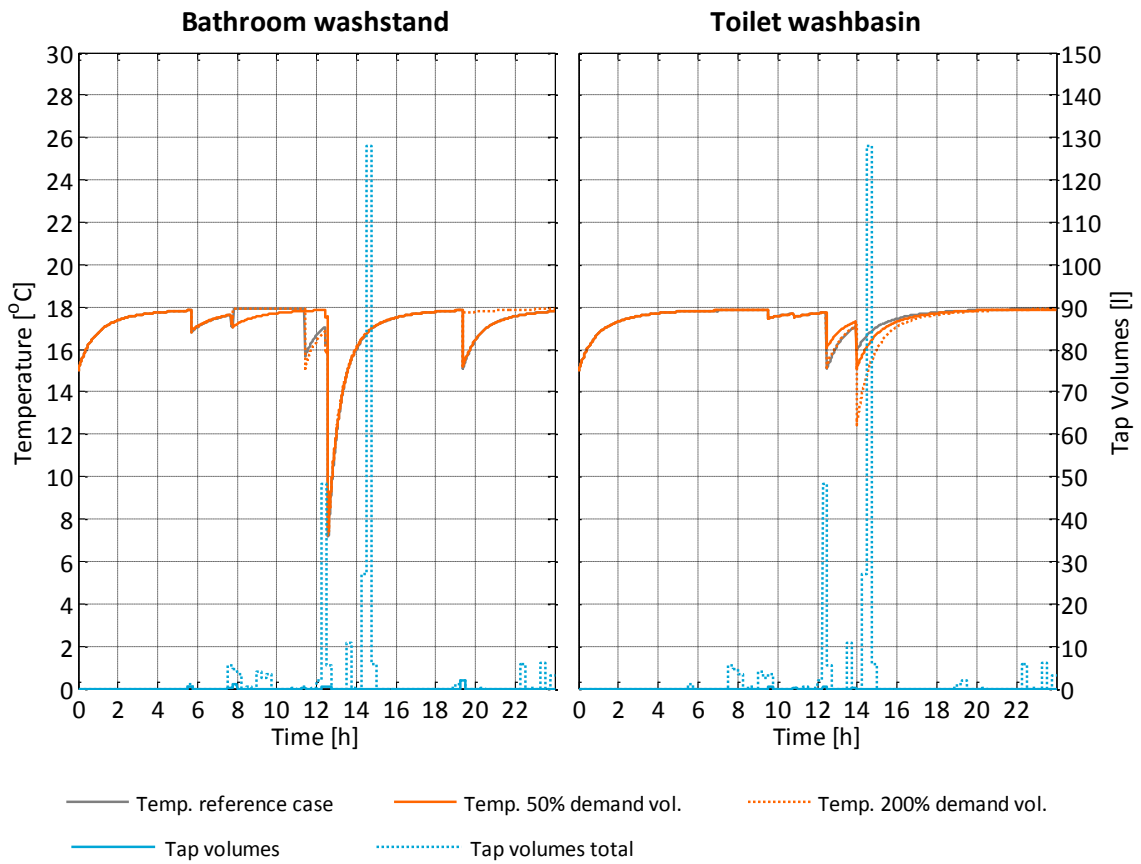


Reference case vs. pipe shaft heating



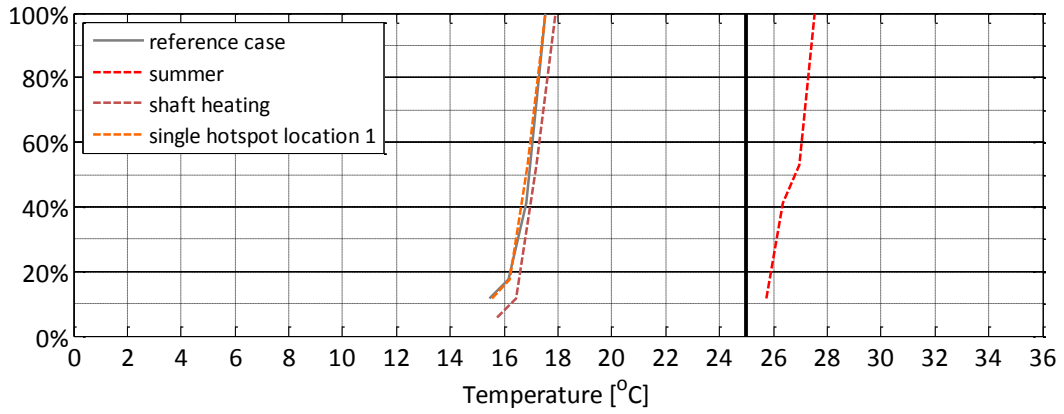


Reference case vs. varying demand volumes

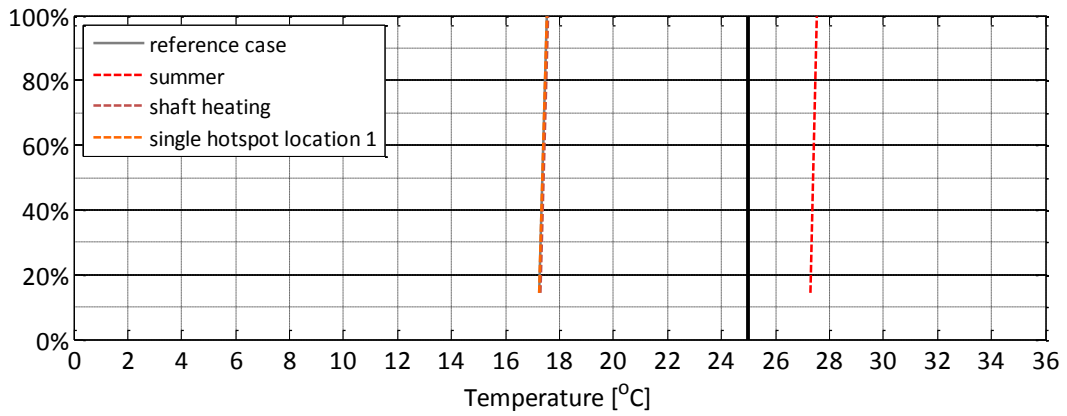


Drinking water temperature during demand

Bathroom washstand

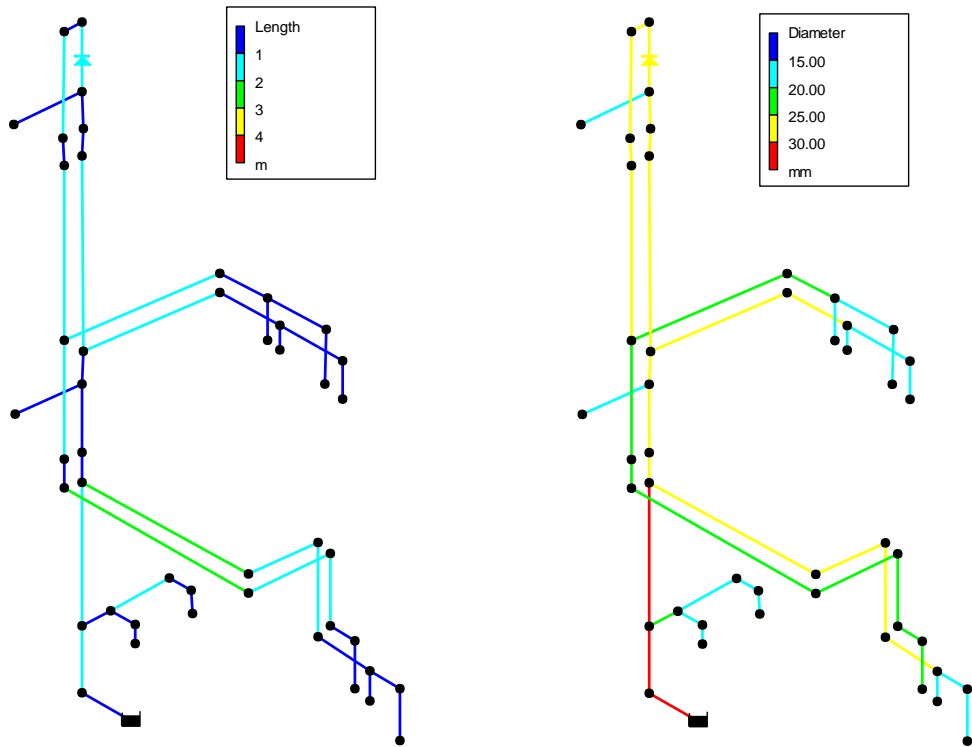


Toilet washbasin

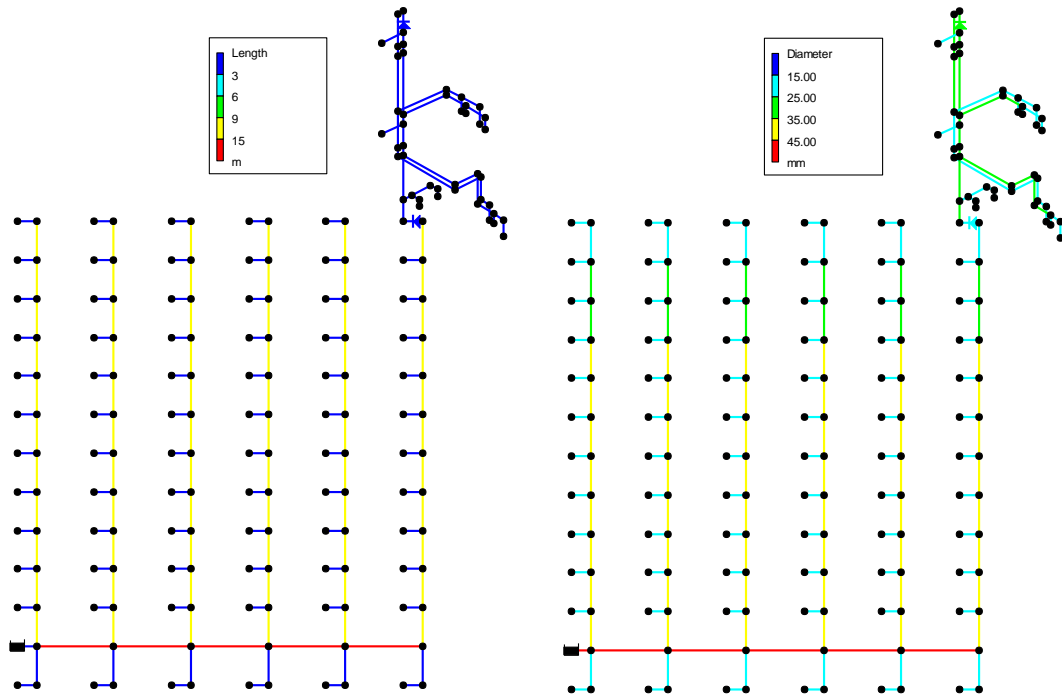


Pipe characteristics of used networks

Basic network layout



Apartment network layout



Annex IV

MSX code

The specific script which was used to calculate the results shown in chapter 0 is mentioned below. This script can be used as MSX file when it is saved in a notepad file using the .msx extension.

```
[TITLE]
Temperature modeling for domestic drinking water systems

[OPTIONS]
RATE_UNITS      SEC
SOLVER          EUL
COMPILER        VC
TIMESTEP        10

[SPECIES]
BULK            TEMP MG
BULK            AGE MG
BULK            numMO MG          ;kve/l

[COEFFICIENTS]

;all coefficients are determined at 20 deg C

CONSTANT        g          9.81          ;m/s2 gravitational acceleration
CONSTANT        rho_w      1000         ;kg/m3 water density
CONSTANT        rho_a      1.205        ;kg/m3 density of air
CONSTANT        cp_w       4185         ;J/(kgK) heat capacity of water
CONSTANT        mu_w       0.001        ;Pa s dynamic viscosity of water
CONSTANT        mu_a       0.000018    ;Pa s dynamic viscosity of air
CONSTANT        kv_a       2.231E-10    ;m2/s kinematic viscosity of air raised
                                           by power two
CONSTANT        Pr_w       7.01         ;- Prandtl number for water
CONSTANT        Pr_a       0.713        ;- Prandtl number for air
CONSTANT        labda_w    0.6           ;W/(m K) thermal conductivity of water
CONSTANT        labda_a    0.0257       ;W/(m K) thermal conductivity of air
CONSTANT        beta_a     0.0034       ;1/K air cubic expansion coefficient
CONSTANT        d_air      0.005        ;m air layer around concealed
                                           pipes
CONSTANT        tt         3600         ;- help variable to compensate MSX
                                           error
CONSTANT        T_opt      37           ;K optimal growth temperature MO
CONSTANT        T_diff     96.8         ;- diff between T_opt & T_min
                                           to power 2 times 0.2
PARAMETER       d_pipe     0.001        ;m pipe thickness
```

```

PARAMETER    T_env    18          ;K environment temperature
PARAMETER    labda_p  403         ;W/(m K) thermal conductivity of pipe
                                     material (copper, 0.16 for PVC-C)
PARAMETER    VV       1          ;- equals 1 for vertical pipes
PARAMETER    EN       0          ;- equals 1 pipes which are installed in
                                     walls, 0 for 'free' pipes
PARAMETER    LL       1          ;- length of vertical pipe (specified
                                     below)

[TERMS]
;Nusselt number for moving fluid
Nu_fl        step(Re - 10)*5.8 + step(10 - Re)*step(Re - 2300)*3.66 +
               step(2300 - Re)*(0.023*Re^0.8*Pr_w^(0.3333))

[PIPES]
RATE         TEMP     4 * (T_env - TEMP) / (D*rho_w*cp_w) *
               1/(D/(Nu_fl*labda_w) + d_pipe/labda_p - (EN-
               1)*D/((0.59 * ((g*beta_a * (step((T_env-TEMP)-
               0)*(T_env-TEMP) + step(0-(T_env-TEMP))*(TEMP-T_env)) *
               (VV*LL-(VV-1)*D)^3/kv_a) * Pr_a) ^ 0.25)*labda_a) +
               EN*(d_air/labda_a))

RATE         AGE      1 / tt

RATE         numMO    0.0000115 * exp(-(TEMP - T_opt)^2/T_diff)*numMO

[SOURCES]
SETPOINT     45        TEMP      55

[QUALITY]
GLOBAL       TEMP      15
GLOBAL       AGE       0
GLOBAL       numMO     250

NODE         9         TEMP      5
NODE         45        TEMP      55
NODE         45        numMO     0

[PARAMETERS]
;list of pipes which are horizontal

;list of pipe lengths (vertical pipes)

;list of pipes which are influenced by a deflected T_env (i.e. through
parallel hot water pipes)

;list of pipes which are installed in walls

```

```
[REPORT]
NODES      ALL
LINKS      ALL
SPECIES    TEMP      YES
SPECIES    AGE       YES
SPECIES    numMO     YES

FILE       E:\AFST\WORKMAP\msx_rep.txt
```

Comments on MSX code

- The option "RATE_UNITS" is in the manual mentioned to be "TIME_UNITS". However, the latter is not understood by MSX.
- The option "VC" under [OPTIONS] can only be activated if a Visual Basic compiler is installed *and* the environment variables of the computer are supplemented with environment variables from the Visual Basic compiler. The latter is *not* explained by the MSX manual and can be fixed in the menu "advanced system settings" in the system menu (for Windows platforms).
- T_env, VV, EN and LL are parameters and can therefore be changed on pipe basis in the [PARAMETERS] section.
- To clarify the RATE expression for the TEMP variable the expression was partly colored: the blue text makes the model valid for both free and concealed pipes, the red text is the definition of the absolute value of the potential between the water temperature and the environment temperature and the green text is used to make the model valid both for horizontal (which have the diameter as characteristic length) and vertical pipes (which have the absolute length as characteristic length).

Feedback on use of the EPANET MSX

Since MSX is originally designed for (bio)chemical decay of substances one has to be careful when using MSX for other applications. Modeling complex processes like natural convection in MSX is a tough job since the user has several (mathematical) boundaries. The most important ones of these which were encountered by the author are listed below:

- During the attempt to model a dynamic room temperature as an input for the temperature it was found the option MSX allows to add patterns can only be coupled to a node under the [SOURCES] section which means something is added. This implies the temperature could only change in positive direction. The modeling of a dynamic environment temperature by using a pattern was therefore not possible within MSX.
- The possibility to change parameters in the [PARAMETERS] section is only valid for parameters which are used in the [PIPES] section in a RATE expression. Parameters which are used in FORMULA expressions cannot be changed afterwards.
- MSX contains a bug when dividing a number by another number as RATE function. If e.g. the water age is modeled like `RATE AGE 1/3600` the result will be zero for every time step. If it is defined as `RATE AGE 1/a` where `a` is a constant the expression is accepted by MSX.

Input parameters

Material properties

The properties of the different pipe materials are listed below:

Material	Thermal conductivity coefficient [W/(m·K)]
Copper	403
PVC-C	0.16

Water properties

Prandtl number, density, viscosity, heat capacity and thermal conductivity

Material	Unit	Value
Prandtl number	-	7
Density	kg/m ³	1000
Viscosity	Pa·s	0.001
Heat capacity	J/(kg·K)	4185
Thermal conductivity	W/(m·K)	0.6

Curriculum Vitae author

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Sep. 2001 – Jul. 2007 Gymnasium, profile Nature and Technics
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Experience

Jan. 2013 – Jul. 2013 KWR Watercycle Research Institute, Nieuwegein
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Subject: *Drinking water temperature modeling in domestic systems*

Jan. 2008 – current Korps Nationale Reserve (Natres), Nieuw Milligen
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Subject: *indexing and monitoring of vulnerable customers*

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Function: cleaner

Others

Sep. 2007 – Jul. 2012

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Languages

	Spoken	Written
Dutch	Good	Good
Engels	Good	Good

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